in above, $\hat{n}$ is outward pointing normal to surface S
$d\vec{l}$ is differential tangent to curve C bounding surface S

<u>Proof</u> that (1) and (2) follow from (*)

<u>First</u> Note that $\boxed{\dfrac{\vec{r}-\vec{r}'}{|\vec{r}-\vec{r}'|^3} = -\vec{\nabla}\left(\dfrac{1}{|\vec{r}-\vec{r}'|}\right)}$

to see this, let $\vec{\mathscr{r}} = \vec{r}-\vec{r}'$, and do the calculation in spherical coords centered at $\vec{\mathscr{r}}=0$.

$$\frac{\vec{r}-\vec{r}'}{|\vec{r}-\vec{r}'|^3} = \frac{\hat{\mathscr{r}}}{\mathscr{r}^2}$$

$$-\vec{\nabla}\left(\frac{1}{|\vec{r}-\vec{r}'|}\right) = -\vec{\nabla}\frac{1}{\mathscr{r}}$$

since $\vec{\mathscr{r}} = \vec{r}-\vec{r}'$, we have $\vec{\nabla}$ (which differentiates with respect to $\vec{r}$) is the same as $\vec{\nabla}_{\mathscr{r}}$ (which differentiates with respect to $\vec{\mathscr{r}}$)

So $\quad -\vec{\nabla}\left(\frac{1}{\mathscr{r}}\right) = -\hat{\mathscr{r}}\frac{d}{d\mathscr{r}}\left(\frac{1}{\mathscr{r}}\right)$ using $\vec{\nabla}$ in spherical coords

$$= \frac{\hat{\mathscr{r}}}{\mathscr{r}^2}$$

So from Coulomb we have

$$\vec{E}(\vec{r}) = k_1\int d^3r'\,\rho(\vec{r}')\,\frac{\vec{r}-\vec{r}'}{|\vec{r}-\vec{r}'|^3}$$

$$= -\vec{\nabla}\left(k_1\int d^3r'\,\frac{\rho(\vec{r}')}{|\vec{r}-\vec{r}'|}\right)$$ $\vec{E}$ is gradient of scalar function

$\Rightarrow \boxed{\vec{\nabla}\times\vec{E} = 0}$ since the curl of a gradient always vanishes
$\vec{\nabla}\times\vec{\nabla}\phi = 0$ for any scalar function

$$\vec{\nabla}\cdot\vec{E} = -\nabla^2\left(k_1\int d^3r'\,\frac{\rho(r')}{|\vec{r}-\vec{r}\,'|}\right) \qquad \text{where } \nabla^2 = \vec{\nabla}\cdot\vec{\nabla}$$

Consider

$$\nabla^2\left(\frac{1}{|\vec{r}-\vec{r}\,'|}\right)$$

as before, define $\vec{\imath} = \vec{r}-\vec{r}\,'$, so $\vec{\nabla}_r = \vec{\nabla}_{\imath}$, and go to spherical coords centered at $\vec{\imath}=0$.

$$\nabla^2\left(\frac{1}{|\vec{r}-\vec{r}\,'|}\right) = \nabla_{\imath}^2\left(\frac{1}{\imath}\right)$$ use expression for ∇^2 in spherical coords

$$= \frac{1}{\imath}\frac{d^2}{d\imath^2}\,\imath\left(\frac{1}{\imath}\right)$$

$$= \begin{cases} 0\,! & \text{for } \imath \neq 0 \\ \text{singular} & \text{at } \imath = 0 \end{cases}$$

So

$\nabla^2\left(\frac{1}{\imath}\right)$ vanishes everywhere except at $\imath=0$

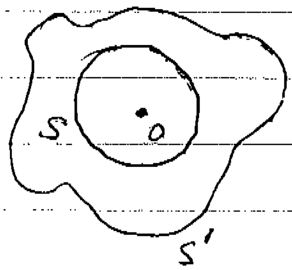
to see what happens at $\imath=0$, consider integrating over a sphere V of radius R centered at the origin

$$\int_V d^3r\,\nabla^2\left(\frac{1}{\imath}\right) = \int_V d^3r\,\vec{\nabla}\cdot\vec{\nabla}\left(\frac{1}{\imath}\right) = \oint_S da\,\hat{n}\cdot\vec{\nabla}\left(\frac{1}{\imath}\right)$$ using Gauss' Theorem

integrand $\hat{n}\cdot\vec{\nabla}\left(\frac{1}{\imath}\right) = \frac{d}{d\imath}\left(\frac{1}{\imath}\right) = -\frac{1}{\imath^2}$ is constant on surface S so

$$\oint_S da\,\hat{n}\cdot\vec{\nabla}\left(\frac{1}{\imath}\right) = 4\pi R^2\left(\frac{-1}{R^2}\right) = -4\pi$$

Above was integrating over a sphere, but we would get same result if integrated over any volume containing $\vec{r}=0$



S is sphere of radius R
S' is any surface

let $\tilde{V}'$ be volume between S and S'.
Then by Gauss theorem

$$\int_{\tilde{V}'} d^3r\ \vec{\nabla}\cdot\vec{\nabla}\left(\frac{1}{r}\right) = \oint_{S'} da\ \hat{n}\cdot\vec{\nabla}\left(\frac{1}{r}\right) - \oint_{S} da\ \hat{n}\cdot\vec{\nabla}\left(\frac{1}{r}\right)$$

$$= 0 \quad \text{since } \nabla^2\left(\frac{1}{r}\right) = 0 \text{ everywhere in } V'$$

$$\Rightarrow \oint_{S'} da\ \hat{n}\cdot\vec{\nabla}\left(\frac{1}{r}\right) = \oint_{S} da\ \hat{n}\cdot\vec{\nabla}\left(\frac{1}{r}\right)$$

$$\Rightarrow \int_{V'} d^3r\ \nabla^2\left(\frac{1}{r}\right) = \int_{V} d^3r\ \nabla^2\left(\frac{1}{r}\right)$$

V' bounded by S' $\qquad$ V bounded by S

So we conclude: for any volume V
$$\int_V d^3r\ \nabla^2\left(\frac{1}{r}\right) = \begin{cases} -4\pi & \text{if } \vec{r}=0 \text{ in } V \\ 0 & \text{if } \vec{r}=0 \text{ not in } V \end{cases}$$

$$\Rightarrow \nabla^2\left(\frac{1}{r}\right) = -4\pi\,\delta(\vec{r}) \quad \text{Dirac delta function}$$

$$\boxed{\nabla^2\left(\frac{1}{|\vec{r}-\vec{r}'|}\right) = -4\pi\,\delta\left(|\vec{r}-\vec{r}'|\right)}$$

So now

acts only on $\vec{r}$

$$\vec{\nabla}\cdot\vec{E} = -k_1\int d^3r'\,\rho(r')\,\nabla^2\left(\frac{1}{|\vec{r}-\vec{r}'|}\right)$$

$$= -k_1\int d^3r'\,\rho(\vec{r}')\,(-4\pi)\,\delta(\vec{r}-\vec{r}')$$

$$= 4\pi k_1\,\rho(\vec{r}) \qquad \text{key property of } \delta\text{-function}$$

proof is done!

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we have shown that

$$\vec{E}(\vec{r}) = k_1\int d^3r'\,\rho(\vec{r}')\,\frac{\vec{r}-\vec{r}'}{|\vec{r}-\vec{r}'|} \Rightarrow \begin{cases} \vec{\nabla}\cdot\vec{E} = 4\pi k_1\rho \\ \vec{\nabla}\times\vec{E} = 0 \end{cases}$$

is the reverse true? ie is the formulation in terms of partial differential equations completely equivalent to Coulomb's Law? Yes! because of Helmholtz's Theorem

Helmholtz Theorem of vector calculus — if one specifies the divergence and curl of a vector function, and boundary conditions (here $E \to 0$ as $r \to \infty$ and one is away from all charges), then vector function is uniquely determined

Magnetostatics

Lorentz Force

a charge q, in motion with velocity $\vec{v}$, feels the force

$$\vec{F} = q(\vec{E} + k_4 \, \vec{v} \times \vec{B}) \quad \leftarrow \text{Lorentz force}$$

$\vec{B}$ is the magnetic field at the position of the charge. k_4 is a universal constant.

Just as the constant k_1 fixed the units of charge q, the constant k_4 can be viewed as fixing the units of B magnetic field. By choosing the units of q and B appropriately, we are free to choose any values for k_1 and k_4.

Magnetic field $\vec{B}$ is generated by moving charge. A charge q' with velocity $\vec{v}'$ ($v' \ll c$) located at the origin $\vec{r}'=0$ produces a magnetic field at position $\vec{r}$,

holds only nonrelativistically →

$$\vec{B}(\vec{r}) = k_5 \, q' \, \frac{\vec{v}' \times \vec{r}}{r^3} = \frac{k_5}{k_1} \, \vec{v}' \times \vec{E}(\vec{r})$$

k_5 is a universal constant. we will see that it cannot be chosen independently of k_1 and k_4. (since k_1 fixed units of q, and k_4 fixed units of $\vec{B}$, there are no further new quantities whose units could be adjusted to allow us to fix k_5 arbitrarily)

The force on a charge q at position $\vec{r}$, moving with velocity $\vec{v}$, due to a charge q' at the origin moving with velocity $\vec{v}'$ is, in non-relativistic limit $(v, v' \ll c)$ is,

$$\vec{F} = k_1 q q' \frac{\vec{r}}{r^3} + k_4 k_5 q q' \vec{v} \times \frac{(\vec{v}' \times \vec{r})}{r^3}$$

$\uparrow$ Coulomb force $\qquad$ $\uparrow$ magnetic analog of Coulomb force

The magnetic part is just the point charge equivalent of the Biot-Savart law for the force between current ~~carry~~ carrying wires. If we regard $q\vec{v} = \vec{I}$ as the current of charge q, and $q'\vec{v}' = \vec{I}'$ as the current of charge q', then the magnetic force is $k_4 k_5 \; \vec{I} \times (\vec{I}' \times \frac{\vec{r}}{r^3})$ which is the Biot-Savart Law.

Rewrite above force as

$$\vec{F} = k_1 \left(1 + \frac{k_4 k_5}{k_1} \vec{v} \times \vec{v}' \times \right) \frac{\vec{r}}{r^3} q q'$$

we see that $\left(\frac{k_4 k_5}{k_1}\right)$ has units of $(\text{velocity})^{-2}$

it must be independent of whatever convention one used to choose the units of q or B (ie independent of choices for k_1 and k_4). Experimentally it is found that

$$\left(\frac{k_4 k_5}{k_1}\right) = \frac{1}{c^2}$$

c = speed of light in vacuum

Continuum current density

For charges q_i at positions $\vec{r}_i(t)$ with $\vec{v}_i = \frac{d\vec{r}_i}{dt}$
we define the current density

$$\vec{j}(\vec{r},t) = \sum_i q_i \vec{v}_i(t)\, \delta(\vec{r} - \vec{r}_i(t))$$

units of $\vec{j}$ are $(\text{charge})\left(\frac{\text{length}}{\text{time}}\right)\left(\frac{1}{\text{length}^3}\right) = \left(\frac{\text{charge}}{\text{area}\cdot\text{time}}\right)$

charge per unit area per unit time

For a surface S

$$\int_S da\, \hat{n}\cdot\vec{j} = I$$ current (charge per unit time) passing through surface S

Charge Conservation   vol V bounded by surface S

$$\frac{d}{dt}\int_V d^3r\, \rho(\vec{r},t) = -\oint_S da\, \hat{n}\cdot\vec{j}$$

rate of change of total charge in V = $(-)$ charge flowing out of V through S per unit time

Use $\oint_S da\,\hat{n}\cdot\vec{j} = \int_V d^3r\, \vec{\nabla}\cdot\vec{j} = -\int_V d^3r\, \frac{\partial}{\partial t}\rho(\vec{r},t)$

$\Rightarrow$ local charge conservation

$$\boxed{\frac{\partial \rho}{\partial t} + \vec{\nabla}\cdot\vec{j} = 0}$$

A static situation has $\frac{\partial \rho}{\partial t} = 0$

$\Rightarrow$ <u>magnetostatics</u> is defined by the condition $\underline{\vec{\nabla}\cdot\vec{J} = 0}$

<u>Differential formulation of Biot-Savart</u>

For a set of charges q_i at $\vec{r}_i$ we have

$$\vec{B}(\vec{r}) = \sum_i k_5\, q_i\, \vec{v}_i \times \frac{(\vec{r}-\vec{r}_i)}{|\vec{r}-\vec{r}_i|^3}$$

$$= k_5 \int d^3r'\, \vec{J}(\vec{r}\,') \times \frac{(\vec{r}-\vec{r}\,')}{|\vec{r}-\vec{r}\,'|^3}$$

$$= k_5 \int d^3r'\, \vec{J}(\vec{r}\,') \times \vec{\nabla}\left(\frac{-1}{|\vec{r}-\vec{r}\,'|}\right)$$

$$\vec{B}(\vec{r}) = k_5\, \vec{\nabla} \times \left[\int d^3r'\, \frac{\vec{J}(r')}{|\vec{r}-\vec{r}\,'|}\right]$$

where we used $\vec{\nabla}\times(\vec{A}\varphi) = -\vec{A}\times\vec{\nabla}\varphi$ when $\vec{A}$ is indep of $\vec{r}$

$\Rightarrow$ $\boxed{\vec{\nabla}\cdot\vec{B} = 0}$ since $\vec{\nabla}\cdot(\vec{\nabla}\times\vec{A}) = 0$ for any vector function $\vec{A}$

integral form $\oint_S da\, \hat{n}\cdot\vec{B} = 0$

$$\vec{\nabla}\times\vec{B} = k_5\, \vec{\nabla}\times\left[\vec{\nabla}\times\left(\int d^3r'\, \frac{\vec{J}(\vec{r}\,')}{|\vec{r}-\vec{r}\,'|}\right)\right]$$

use $\vec{\nabla}\times(\vec{\nabla}\times\vec{A}) = \vec{\nabla}(\vec{\nabla}\cdot\vec{A}) - \nabla^2\vec{A}$

$$\vec{\nabla}\times\vec{B} = k_5\,\vec{\nabla}\left[\int d^3r'\;\vec{\nabla}\cdot\left(\frac{\vec{j}(\vec{r}')}{|\vec{r}-\vec{r}'|}\right)\right]$$

$$-k_5\int d^3r'\;\vec{j}(\vec{r}')\,\nabla^2\left(\frac{1}{|\vec{r}-\vec{r}'|}\right)$$

in the 2nd term, $\nabla^2\left(\frac{1}{|\vec{r}-\vec{r}'|}\right) = -4\pi\,\delta(\vec{r}-\vec{r}')$

in the 1st term, $\vec{\nabla}\cdot\frac{\vec{j}(\vec{r}')}{|\vec{r}-\vec{r}'|} = \vec{j}(\vec{r}')\cdot\vec{\nabla}\left(\frac{1}{|\vec{r}-\vec{r}'|}\right)$

$$= -\vec{j}(\vec{r}')\cdot\vec{\nabla}'\left(\frac{1}{|\vec{r}-\vec{r}'|}\right)$$

since $\vec{\nabla} = -\vec{\nabla}'$

So $\int d^3r'\,\vec{\nabla}\cdot\left(\frac{\vec{j}(\vec{r}')}{|\vec{r}-\vec{r}'|}\right) = -\int d^3r'\,\vec{j}(\vec{r}')\cdot\vec{\nabla}'\left(\frac{1}{|\vec{r}-\vec{r}'|}\right)$

integrate by parts $\quad = \int d^3r'\left(\vec{\nabla}'\cdot\vec{j}(r')\right)\left(\frac{1}{|\vec{r}-\vec{r}'|}\right)$
surface term $\to 0$ as
we take surface $\to\infty$
since $\vec{j}\to 0$ as $r\to\infty$

But for <u>magnetostatics</u> $\vec{\nabla}\cdot\vec{j} = 0 \Rightarrow$ only 2nd term remains

Thus, for <u>magnetostatics</u>

$$\vec{\nabla}\times\vec{B} = 4\pi k_5\,\vec{j} \qquad \text{Ampere's law}$$

integral form $\displaystyle\oint_C d\vec{l}\cdot\vec{B} = 4\pi k_5\int_S da\,\hat{n}\cdot\vec{j}$

curve bounding surface

Although above diff eqns were derived starting from a "non-relativistic"