Electricity-Magnetism I

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This is an undergraduate course. Offered in Fall 2013 at Columbia University. Required Course textbook: Griffiths, *Introduction to Electrodynamics.* Office Hours Mon 10:35– 11:35.

Contents

1 Preliminary

Lecture 1 (9/4/13)

There are two aspects of electrodynamics: classical, modern. Histrionically the development of electrodynamics came from two different paths: electricity (studied charges) magnetism (studied magnets). Each of them were put into laws like: Gauss, Ampere, Faraday, etc. Later Maxwell completed the subjects with Maxwell's equations.

The more modern aspect of EM starts from Maxwell equations, showing EM waves propagating at the speed of light, and EM fields are Lorentz invariant, i.e. EM automatically compatible with special relativity. To incorporate EM with quantum mechanics, the subject of Quantum field theory was invent, which started from quantization of EM field.

1.1 Units

The fundamental subject we study is charge. It is carried by some particles, e.g. electrons. When the charge spins, it produces magnetic field, so both E&M are from charges. Recall electric charges are quantized, meaning (1) indivisibility

$$e = 1.6 \times 10^{-19} C \quad C = \text{coulomb}$$

(2) indestructibility, i.e. conserved.

SI v.s. cgs

One can invert another unit for charge esu = static coulomb.

$$1C = 2.997 \times 10^9 esu$$

This conversion will change the units of $\vec{E}$ and $\vec{B}$ as well. More important it changes the form of Lorentz force and Maxwell equations.

SI	cgs
$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$	$\vec{F} = q(\vec{E} + \frac{\vec{v}}{c} \times \vec{B})$
$\vec{\nabla} \cdot \vec{E} = \frac{1}{\epsilon_0}\rho$	$\vec{\nabla} \cdot \vec{E} = 4\pi\rho$
$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$	$\vec{\nabla} \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$
$\vec{\nabla} \cdot \vec{B} = 0$	$\vec{\nabla} \cdot \vec{B} = 0$
$\vec{\nabla} \times \vec{B} = \mu_0 \vec{j} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$	$\vec{\nabla} \times \vec{B} = \frac{4\pi}{c}\vec{j} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}$

So the annoying ϵ_0, μ_0 disappear. It become more apparent if we look at Coulomb force. $4\pi\epsilon_0$ becomes 1.

SI	cgs
$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{e}{r^2}\hat{r}$	$\vec{E} = \frac{e}{r^2}\hat{r}$
$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\frac{e}{r}$	$V(\vec{r}) = \frac{e}{r}$

1.2 Review of Vector Analysis

Vector Operation

$$\vec{A} \cdot \vec{B} \qquad \vec{A} \times \vec{B} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ A_x & A_y & A_z \\ B_x & B_x & B_z \end{vmatrix}$$

Vector Coordination

Cartesian

$$\vec{A} = A_x\hat{x} + A_y\hat{y} + A_z\hat{z} = \sum_{i=1}^{3} A_i\hat{e}_i$$

Spherical (r, θ, ϕ)

Cylindrical (s, ϕ, z) where s is the distance $\vec{A}$ projected onto xy plane, so s is not the same as the spherical r. However ϕ is the same.

Simple Vector Algebra

$$\vec{A} \cdot (\vec{B} \times \vec{C}) = \vec{B} \cdot (\vec{C} \times \vec{A}) = \vec{C} \cdot (\vec{A} \times \vec{B})$$

because

$$\vec{A}\cdot(\vec{B}\times\vec{C}) = \begin{vmatrix} A_1 & A_2 & A_3 \\ B_1 & B_2 & B_3 \\ C_1 & C_2 & C_3 \end{vmatrix} = \begin{vmatrix} B_1 & B_2 & B_3 \\ C_1 & C_2 & C_3 \\ A_1 & A_2 & A_3 \end{vmatrix} = ...$$

interchange two rows the det is the same.

BAC-CAB rule

$$\vec{A}\times(\vec{B}\times\vec{C}) = \vec{B}(\vec{A}\cdot\vec{C}) - \vec{C}(\vec{A}\cdot\vec{B})$$

Vector Transform

$$\vec{A} \xrightarrow{U} \vec{A}^p$$

Rotation around $\hat{z}$ by angle ϕ

$$\vec{A} \to \begin{pmatrix} \cos\phi & \sin\phi & \\ -\sin\phi & \cos\phi & \\ & & 1 \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \\ A_3 \end{pmatrix}$$

Point inversion with respect to the origin

$$\vec{A} \to \begin{pmatrix} -1 & & \\ & -1 & \\ & & -1 \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \\ A_3 \end{pmatrix}$$

Mirror reflection about xz plane

$$\vec{A} \to \begin{pmatrix} 1 & & \\ & -1 & \\ & & 1 \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \\ A_3 \end{pmatrix}$$

Mirror reflection is a good test to see there are two different kind of vectors: polar vector and axial vector (pseudo vector). Suppose a top down view counterclockwise current is placed in front of a mirror, one identifies the direction of $\vec{B}$ it produces. Now mirror reflects the whole the system. Current becomes clockwise, and the reflected $\vec{B}$ stays the same. This doesn't agree with Ampere law. We call $\vec{B}$ is an axial vector. Another axial vector is angular momentum $\vec{L}$. They have serious implications, parity violation.

Vector Differential Calculus

Del in Cartesian

$$\nabla = \hat{x}\frac{\partial}{\partial x} + \hat{y}\frac{\partial}{\partial y} + \hat{z}\frac{\partial}{\partial z} \tag{1.1}$$

Gradient

$$\nabla T = \hat{x}\frac{\partial T}{\partial x} + \hat{y}\frac{\partial T}{\partial y} + \hat{z}\frac{\partial T}{\partial z}$$

T some scalar function of space (x, y, z).

Divergence

$$\nabla \cdot \vec{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} \tag{1.2}$$

Curl

$$\nabla \times \vec{v} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ v_x & v_y & v_z \end{vmatrix} = \hat{x}\left(\frac{\partial v_z}{\partial z} - \frac{\partial v_y}{\partial y}\right) + \ldots \tag{1.3}$$

Since ∇ is an operator, the order is important, e.g. use BAC-CAB crudely

$$\nabla \times (\vec{B} \times \vec{C}) = \vec{B}(\nabla \cdot \vec{C}) - \vec{C}(\nabla \cdot \vec{B})$$

This is wrong! Correct way is

$$\begin{aligned} \nabla \times (\vec{B} \times \vec{C}) &= (\nabla \cdot \vec{C})\vec{B} - (\nabla \cdot \vec{B})\vec{C} \\ &= \vec{B}(\nabla \cdot \vec{C}) + (\vec{C} \cdot \nabla)\vec{B} - \vec{C}(\nabla \cdot \vec{B}) - (\vec{B} \cdot \nabla)\vec{C} \end{aligned}$$

Second Derivative:

Laplacian

$$\nabla^2 = \nabla \cdot \nabla = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

Curl of gradient

$$\nabla \times (\nabla T) = \vec{0}$$

because

$$\nabla \times (\nabla T) = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ \frac{\partial T}{\partial x} & \frac{\partial T}{\partial y} & \frac{\partial T}{\partial z} \end{vmatrix} = \hat{x}\left(\frac{\partial^2 T}{\partial y \partial z} - \frac{\partial^2 T}{\partial z \partial y}\right) + \ldots$$

Divergence of curl

$$\nabla \cdot (\nabla \times \vec{v}) = 0$$

because

$$\nabla \cdot (\nabla \times \vec{v}) = \begin{vmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ v_x & v_y & v_z \end{vmatrix} = 0$$

1.3 Integral Calculus of Vectors

Line Integral

Lecture 2 (9/9/13)

We're interested in line integral of gradiant of a scalar field

$$dT = (\nabla T) \cdot d\vec{l}$$

$$\int_A^B (\nabla T) \cdot d\vec{l} = T(B) - T(A)$$

It is path independent. If $A = B$, closed loop

$$\oint (\nabla T) \cdot d\vec{l} = 0$$

Stokes' Thoerm

$$\iint_S (\nabla \times \vec{V}) \cdot d^2\vec{S} = \oint \vec{V} \cdot d\vec{l}$$

Gauss Thoerem

$$\iiint (\nabla \cdot \vec{V}) d^3\tau = \oiint \vec{V} \cdot d^2\vec{S}$$

1.4 Coordniates

Computation will be greatly reduced if we choose the right coordninates for the right problem.

Gradiant

By the line integral, gradient is the directional derivative of T for arbitrary direction $\vec{l}$

$$(\nabla T) \cdot d\vec{l} = \Delta T$$

$$\nabla T = \frac{dT}{d\vec{l}} = \frac{\text{change in } \psi}{\text{arc length in } \hat{n}\text{direction}}$$

Thus

$$\nabla T = \sum \hat{e}_i \frac{1}{h_i} \frac{\partial \psi}{\partial q_i}$$

where h_i is the unit length in $\hat{e}_i$.

∇ of (1.1) in spherical cooridnate

$$\nabla = \hat{r}\frac{\partial}{\partial r} + \hat{\theta}\frac{1}{r}\frac{\partial}{\partial \theta} + \hat{\phi}\frac{1}{r\sin\theta}\frac{\partial}{\partial \phi}$$

Rigious proof

$$\begin{cases} x = r\sin\theta\cos\phi \\ y = r\sin\theta\sin\phi \\ z = r\cos\theta \end{cases} \quad \text{or} \quad \begin{cases} r = \sqrt{x^2+y^2+z^2} \\ \cos\theta = \frac{z}{r} \\ \cos\phi = \frac{x}{r\sin\theta} \end{cases}$$

$$\begin{aligned} \hat{r} &= (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta) \\ \hat{\theta} &= (\cos\theta\cos\phi, \cos\theta\sin\phi, -\sin\theta) \\ \hat{\phi} &= (-\sin\phi, \cos\phi, 0) \end{aligned}$$

or in matrix form

$$\begin{pmatrix} \hat{r} \\ \hat{\theta} \\ \hat{\phi} \end{pmatrix} = \begin{pmatrix} \sin\theta\cos\phi & \sin\theta\sin\phi & \cos\theta \\ \cos\theta\cos\phi & \cos\theta\sin\phi & -\sin\theta \\ -\sin\phi & \cos\phi & 0 \end{pmatrix} \begin{pmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{pmatrix} = O \begin{pmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{pmatrix}$$

Which is an orthogonal matrix, so the inverse is just O^T

$$\begin{pmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{pmatrix} = \begin{pmatrix} \sin\theta\cos\phi & \cos\theta\cos\phi & -\sin\phi \\ \sin\theta\sin\phi & \cos\theta\sin\phi & \cos\phi \\ \cos\theta & -\sin\theta & 0 \end{pmatrix} \begin{pmatrix} \hat{r} \\ \hat{\theta} \\ \hat{\phi} \end{pmatrix} = O^T \begin{pmatrix} \hat{r} \\ \hat{\theta} \\ \hat{\phi} \end{pmatrix}$$

solve

$$\begin{aligned}
\frac{\partial r}{\partial x} &= \frac{x}{r} = \sin\theta\cos\phi \\
\frac{\partial \theta}{\partial x} &= \frac{zx}{r^3\sin\theta} = \frac{\cos\theta\cos\phi}{r} \\
\frac{\partial \phi}{\partial x} &= \frac{-1 + \sin^2\theta\cos^2\phi + \cos^2\theta\cos^2\phi}{r\sin\theta\sin\phi} = -\frac{\sin\phi}{r\sin\theta}
\end{aligned}$$

note that $\frac{\partial r}{\partial x} \neq \frac{1}{\frac{\partial x}{\partial r}}$. In fact $\frac{\partial r}{\partial x} = \frac{\partial x}{\partial r} = \sin\theta\cos\phi$. Convince self by drawing and recall $\partial r/\partial x$ means fix y, z constant.

$$\begin{aligned}
\frac{\partial r}{\partial y} &= \frac{y}{r} = \sin\theta\sin\phi \\
\frac{\partial \theta}{\partial y} &= \frac{zy}{r^3\sin\theta} = \frac{\cos\theta\sin\phi}{r} \\
\frac{\partial \phi}{\partial y} &= \frac{\sin^2\theta\sin\phi\cos\phi + \cos^2\theta\sin\phi\cos\phi}{r\sin\theta\sin\phi} = \frac{\cos\phi}{r\sin\theta}
\end{aligned}$$

$$\begin{aligned}
\frac{\partial r}{\partial z} &= \frac{z}{r} = \cos\theta \\
\frac{\partial \theta}{\partial z} &= -\frac{\sin\theta}{r} \\
\frac{\partial \phi}{\partial z} &= 0
\end{aligned}$$

Since

$$\begin{pmatrix} \frac{\partial T}{\partial x} \\ \frac{\partial T}{\partial y} \\ \frac{\partial T}{\partial z} \end{pmatrix} = \begin{pmatrix} \frac{\partial r}{\partial x} & \frac{\partial \theta}{\partial x} & \frac{\partial \phi}{\partial x} \\ \frac{\partial r}{\partial y} & \frac{\partial \theta}{\partial y} & \frac{\partial \phi}{\partial y} \\ \frac{\partial r}{\partial z} & \frac{\partial \theta}{\partial z} & \frac{\partial \phi}{\partial z} \end{pmatrix} \begin{pmatrix} \frac{\partial T}{\partial r} \\ \frac{\partial T}{\partial \theta} \\ \frac{\partial T}{\partial \phi} \end{pmatrix}$$

$$\begin{aligned}
\nabla T &= (\hat{x}, \hat{y}, \hat{z}) \begin{pmatrix} \frac{\partial T}{\partial x} \\ \frac{\partial T}{\partial y} \\ \frac{\partial T}{\partial z} \end{pmatrix} = (\hat{r}, \hat{\theta}, \hat{\phi}) O \begin{pmatrix} \frac{\partial r}{\partial x} & \frac{\partial \theta}{\partial x} & \frac{\partial \phi}{\partial x} \\ \frac{\partial r}{\partial y} & \frac{\partial \theta}{\partial y} & \frac{\partial \phi}{\partial y} \\ \frac{\partial r}{\partial z} & \frac{\partial \theta}{\partial z} & \frac{\partial \phi}{\partial z} \end{pmatrix} \begin{pmatrix} \frac{\partial T}{\partial x} \\ \frac{\partial T}{\partial y} \\ \frac{\partial T}{\partial z} \end{pmatrix} \\
&= (\hat{r}, \hat{\theta}, \hat{\phi}) \begin{pmatrix} \sin\theta\cos\phi & \sin\theta\sin\phi & \cos\theta \\ \cos\theta\cos\phi & \cos\theta\sin\phi & -\sin\theta \\ -\sin\phi & \cos\phi & 0 \end{pmatrix} \begin{pmatrix} \sin\theta\cos\phi & \frac{\cos\theta\cos\phi}{r} & -\frac{\sin\phi}{r\sin\theta} \\ \sin\theta\sin\phi & \frac{\cos\theta\sin\phi}{r} & \frac{\cos\phi}{r\sin\theta} \\ \cos\theta & -\frac{\sin\theta}{r} & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial T}{\partial r} \\ \frac{\partial T}{\partial \theta} \\ \frac{\partial T}{\partial \phi} \end{pmatrix} \\
&= \hat{r}\frac{\partial T}{\partial r} + \hat{\theta}\frac{1}{r}\frac{\partial T}{\partial \theta} + \hat{\phi}\frac{1}{r\sin\theta}\frac{\partial T}{\partial \phi}
\end{aligned}$$

∇ of (1.1) in cylindical coodniate

$$\nabla = \hat{s}\frac{\partial}{\partial s} + \hat{\phi}\frac{1}{s}\frac{\partial}{\partial \phi} + \hat{z}\frac{\partial}{\partial z}$$

Riguoous proof

$$\begin{aligned}
\nabla T &= (\hat{x}, \hat{y}, \hat{z}) \begin{pmatrix} \frac{\partial T}{\partial x} \\ \frac{\partial T}{\partial y} \\ \frac{\partial T}{\partial z} \end{pmatrix} \\
&= (\hat{s}, \hat{\phi}, \hat{z}) \begin{pmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\phi & -\frac{\sin\phi}{s} & 0 \\ \sin\phi & \frac{\cos\phi}{s} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \frac{\partial T}{\partial s} \\ \frac{\partial T}{\partial \phi} \\ \frac{\partial T}{\partial z} \end{pmatrix} \\
&= \hat{s}\frac{\partial}{\partial s} + \hat{\phi}\frac{1}{s}\frac{\partial}{\partial \phi} + \hat{z}\frac{\partial}{\partial z}
\end{aligned}$$

Divergent

$\nabla\cdot$ of (1.2) in spherical cooridnate is NOT

$$\nabla\cdot\vec{V} = \frac{\partial}{\partial r}V_r + \frac{1}{r}\frac{\partial}{\partial\theta}V_\theta + \frac{1}{r\sin\theta}\frac{\partial}{\partial\phi}V_\phi$$

By the Gauss law, is defined as the flux per volume, and take limit of volume to zero

$$\begin{aligned}
\oint_{\text{small volume}}\vec{V}\cdot\hat{n}da &= (V_1(q_1+dq_1)dl_2(q_1+dq_1)dl_3(q_1+dq_1) - V_1(q_1)dl_2(q_1)dl_3(q_1) \\
&\quad +V_2(q_2+dq_2)dl_1(q_2+dq_2)dl_3(q_1+dq_1) - V_2(q_2)dl_1(q_2)dl_3(q_2) \\
&\quad +V_3(q_3+dq_3)dl_1(q_3+dq_3)dl_2(q_3+dq_3) - V_3(q_3)dl_1(q_3)dl_2(3_2)) \\
&= \left(\frac{\partial}{\partial q_1}(V_1h_2h_3) + \frac{\partial}{\partial q_2}(V_2h_1h_3) + \frac{\partial}{\partial q_3}(V_3h_1h_2)\right)\delta q_1\delta q_2\delta q_3
\end{aligned}$$

On the other hand

$$\oint_{\text{small volume}}\vec{V}\cdot\hat{n}da = \iiint(\nabla\cdot\vec{V})h_1h_2h_3\delta q_1\delta q_2\delta q_3$$

so

$$\nabla\cdot\vec{V} = \frac{1}{h_1h_2h_3}\left(\frac{\partial}{\partial q_1}(V_1h_2h_3) + \frac{\partial}{\partial q_2}(V_2h_1h_3) + \frac{\partial}{\partial q_3}(V_3h_1h_2)\right)$$

In spherical coordinatte

$$\nabla\cdot\vec{V} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2V_r) + \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta V_\theta) + \frac{1}{r\sin\theta}\frac{\partial}{\partial\phi}(V_\phi)$$

Riguoous proof

Since

$$\begin{aligned}
V_x &= \hat{x}\cdot\vec{V} \\
&= (\sin\theta\cos\phi\hat{r} + \cos\theta\cos\phi\hat{\theta} - \sin\phi\hat{\phi})(V_r\hat{r} + V_\theta\hat{\theta} + V_\phi\hat{\phi})
\end{aligned}$$

thus

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = O^T \begin{pmatrix} V_r \\ V_\theta \\ V_\phi \end{pmatrix}$$

and

$$\begin{pmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{pmatrix} = \begin{pmatrix} \frac{\partial r}{\partial x} & \frac{\partial \theta}{\partial x} & \frac{\partial \phi}{\partial x} \\ \frac{\partial r}{\partial y} & \frac{\partial \theta}{\partial y} & \frac{\partial \phi}{\partial y} \\ \frac{\partial r}{\partial z} & \frac{\partial \theta}{\partial z} & \frac{\partial \phi}{\partial z} \end{pmatrix} \begin{pmatrix} \frac{\partial}{\partial r} \\ \frac{\partial}{\partial \theta} \\ \frac{\partial}{\partial \phi} \end{pmatrix}$$

$$\begin{aligned}
\nabla \cdot \vec{V} &= \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right) \cdot \begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} \\
&= \left\langle \begin{pmatrix} \sin\theta\cos\phi & \frac{\cos\theta\cos\phi}{r} & -\frac{\sin\phi}{r\sin\theta} \\ \sin\theta\sin\phi & \frac{\cos\theta\sin\phi}{r} & \frac{\cos\phi}{r\sin\theta} \\ \cos\theta & -\frac{\sin\theta}{r} & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial}{\partial r} \\ \frac{\partial}{\partial \theta} \\ \frac{\partial}{\partial \phi} \end{pmatrix}, \begin{pmatrix} \sin\theta\cos\phi & \cos\theta\cos\phi & -\sin\phi \\ \sin\theta\sin\phi & \cos\theta\sin\phi & \cos\phi \\ \cos\theta & -\sin\theta & 0 \end{pmatrix} \begin{pmatrix} V_r \\ V_\theta \\ V_\phi \end{pmatrix} \right. \\
&= \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 V_r) + \frac{1}{r\sin\theta}\frac{\partial}{\partial \theta}(\sin\theta V_\theta) + \frac{1}{r\sin\theta}\frac{\partial}{\partial \phi}(V_\phi)
\end{aligned}$$

In cylindical coodniate

$$\begin{pmatrix} & \\ & \\ & 0 \end{pmatrix}$$

$$\nabla = \hat{s}\frac{\partial}{\partial s} + \hat{\phi}\frac{1}{s}\frac{\partial}{\partial \phi} + \hat{z}\frac{\partial}{\partial z}$$

Curl

∇ of (1.3) in spherical cooridnate

$$\nabla = \hat{r}\frac{\partial}{\partial r} + \hat{\theta}\frac{1}{r}\frac{\partial}{\partial \theta} + \hat{\phi}\frac{1}{r\sin\theta}\frac{\partial}{\partial \phi}$$

in cylindical coodniate

$$\nabla = \hat{s}\frac{\partial}{\partial s} + \hat{\phi}\frac{1}{s}\frac{\partial}{\partial \phi} + \hat{z}\frac{\partial}{\partial z}$$

1.5 Dirac Delta Function

1.6 Potential & Vector field

2 Electrostatics

2.1 Gauss Law

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