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**BASIC EQUATIONS OF ELECTRODYNAMICS**

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**Maxwell's Equations**

In General:

$$\nabla \cdot \vec{E} = \frac{1}{\epsilon_0} \rho$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

In Matter:

$$\nabla \cdot \vec{D} = \rho_f$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{H} = \vec{J}_f + \frac{\partial \vec{D}}{\partial t}$$

**Auxiliary Fields**

Definitions:

$$\vec{D} = \epsilon_0 \vec{E} + \vec{P}$$

$$\vec{H} = \frac{1}{\mu_0} \vec{B} - \vec{M}$$

Linear Media:

$$\vec{P} = \epsilon_0 \chi_e \vec{E}, \quad \vec{D} = \epsilon \vec{E}$$

$$\vec{M} = \chi_m \vec{H}, \quad \vec{H} = \frac{1}{\mu} \vec{B}$$

**Potentials**

$$\vec{E} = -\nabla V - \frac{\partial \vec{A}}{\partial t}, \quad \vec{B} = \nabla \times \vec{A}$$

**Lorentz Force Law**

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

**Energy**

$$\text{Energy: } U = \frac{1}{2} \int \left( \epsilon_0 E^2 + \frac{1}{\mu_0} B^2 \right) d\tau$$

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**FUNDAMENTAL CONSTANTS**

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$$\epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2 / \text{Nm}^2$$

(permittivity of free space)

$$\mu_0 = 4\pi \times 10^{-7} \text{ N/A}^2$$

(permeability of free space)

$$e = 1.60 \times 10^{-19} \text{ C}$$

(charge of the electron)

$$m = 9.11 \times 10^{-31} \text{ kg}$$

(mass of the electron)

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**SPHERICAL AND CYLINDRICAL COORDINATES**

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**Spherical**

$$x = r \sin \theta \cos \phi$$

$$y = r \sin \theta \sin \phi$$

$$z = r \cos \theta$$

$$\hat{x} = \sin \theta \cos \phi \hat{r} + \cos \theta \cos \phi \hat{\theta} - \sin \phi \hat{\phi}$$

$$\hat{y} = \sin \theta \sin \phi \hat{r} + \cos \theta \sin \phi \hat{\theta} + \cos \phi \hat{\phi}$$

$$\hat{z} = \cos \theta \hat{r} - \sin \theta \hat{\theta}$$

**Cylindrical**

$$x = s \cos \phi$$

$$y = s \sin \phi$$

$$z = z$$

$$\hat{x} = \cos \phi \hat{s} - \sin \phi \hat{\phi}$$

$$\hat{y} = \sin \phi \hat{s} + \cos \phi \hat{\phi}$$

$$\hat{z} = \hat{z}$$

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**FUNDAMENTAL THEOREMS**

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$$\text{Gradient Theorem: } \int_a^b (\nabla f) \cdot d\vec{l} = f(\vec{b}) - f(\vec{a})$$

$$\text{Divergence Theorem: } \int (\nabla \cdot \vec{A}) d\tau = \oint \vec{A} \cdot d\vec{a}$$

$$\text{Curl Theorem: } \int (\nabla \times \vec{A}) \cdot d\vec{a} = \oint \vec{A} \cdot d\vec{l}$$

## VECTOR DERIVATIVES

**Cartesian.**  $d\vec{l} = dx \hat{x} + dy \hat{y} + dz \hat{z}$ ;  $d\tau = dx dy dz$

$$\text{Gradient: } \vec{\nabla} t = \frac{\partial t}{\partial x} \hat{x} + \frac{\partial t}{\partial y} \hat{y} + \frac{\partial t}{\partial z} \hat{z}$$

$$\text{Divergence: } \vec{\nabla} \cdot \mathbf{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}$$

$$\text{Curl: } \vec{\nabla} \times \mathbf{v} = \left( \frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z} \right) \hat{x} + \left( \frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x} \right) \hat{y} + \left( \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} \right) \hat{z}$$

$$\text{Laplacian: } \nabla^2 t = \frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2}$$

**Spherical.**  $d\vec{l} = dr \hat{r} + r d\theta \hat{\theta} + r \sin\theta d\phi \hat{\phi}$ ;  $d\tau = r^2 \sin\theta dr d\theta d\phi$

$$\text{Gradient: } \vec{\nabla} t = \frac{\partial t}{\partial r} \hat{r} + \frac{1}{r} \frac{\partial t}{\partial \theta} \hat{\theta} + \frac{1}{r \sin\theta} \frac{\partial t}{\partial \phi} \hat{\phi}$$

$$\text{Divergence: } \vec{\nabla} \cdot \mathbf{v} = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 v_r) + \frac{1}{r \sin\theta} \frac{\partial}{\partial \theta} (\sin\theta v_\theta) + \frac{1}{r \sin\theta} \frac{\partial v_\phi}{\partial \phi}$$

$$\text{Curl: } \vec{\nabla} \times \mathbf{v} = \frac{1}{r \sin\theta} \left[ \frac{\partial}{\partial \theta} (\sin\theta v_\phi) - \frac{\partial v_\phi}{\partial \phi} \right] \hat{r} + \frac{1}{r} \left[ \frac{1}{\sin\theta} \frac{\partial v_r}{\partial \phi} - \frac{\partial}{\partial r} (r v_\phi) \right] \hat{\theta} + \frac{1}{r} \left[ \frac{\partial}{\partial r} (r v_\theta) - \frac{\partial v_r}{\partial \theta} \right] \hat{\phi}$$

$$\text{Laplacian: } \nabla^2 t = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial t}{\partial r} \right) + \frac{1}{r^2 \sin\theta} \frac{\partial}{\partial \theta} \left( \sin\theta \frac{\partial t}{\partial \theta} \right) + \frac{1}{r^2 \sin^2\theta} \frac{\partial^2 t}{\partial \phi^2}$$

**Cylindrical.**  $d\vec{l} = ds \hat{s} + s d\phi \hat{\phi} + dz \hat{z}$ ;  $d\tau = s ds d\phi dz$

$$\text{Gradient: } \vec{\nabla} t = (\partial t / \partial s) \hat{s} + (1/s)(\partial t / \partial \phi) \hat{\phi} + (\partial t / \partial z) \hat{z}$$

$$\text{Divergence: } \vec{\nabla} \cdot \mathbf{v} = \frac{1}{s} \frac{\partial}{\partial s} (s v_s) + \frac{1}{s} \frac{\partial v_\phi}{\partial \phi} + \frac{\partial v_z}{\partial z}$$

$$\text{Curl: } \vec{\nabla} \times \mathbf{v} = \left[ \frac{1}{s} \frac{\partial v_z}{\partial \phi} - \frac{\partial v_\phi}{\partial z} \right] \hat{s} + \left[ \frac{\partial v_s}{\partial z} - \frac{\partial v_z}{\partial s} \right] \hat{\phi} + \frac{1}{s} \left[ \frac{\partial}{\partial s} (s v_\phi) - \frac{\partial v_s}{\partial \phi} \right] \hat{z}$$

$$\text{Laplacian: } \nabla^2 t = \frac{1}{s} \frac{\partial}{\partial s} \left( s \frac{\partial t}{\partial s} \right) + \frac{1}{s^2} \frac{\partial^2 t}{\partial \phi^2} + \frac{\partial^2 t}{\partial z^2}$$

## VECTOR IDENTITIES

### Triple Products

$$(1) \vec{A} \cdot (\vec{B} \times \vec{C}) = \vec{B} \cdot (\vec{C} \times \vec{A}) = \vec{C} \cdot (\vec{A} \times \vec{B})$$

$$(2) \vec{A} \times (\vec{B} \times \vec{C}) = \vec{B}(\vec{A} \cdot \vec{C}) - \vec{C}(\vec{A} \cdot \vec{B})$$

### Product Rules

$$(3) \vec{\nabla}(fg) = f(\vec{\nabla}g) + g(\vec{\nabla}f)$$

$$(4) \vec{\nabla}(\vec{A} \cdot \vec{B}) = \vec{A} \times (\vec{\nabla} \times \vec{B}) + \vec{B} \times (\vec{\nabla} \times \vec{A}) + (\vec{A} \cdot \vec{\nabla})\vec{B} + (\vec{B} \cdot \vec{\nabla})\vec{A}$$

$$(5) \vec{\nabla} \cdot (f\vec{A}) = f(\vec{\nabla} \cdot \vec{A}) + \vec{A} \cdot (\vec{\nabla}f)$$

$$(6) \vec{\nabla} \cdot (\vec{A} \times \vec{B}) = \vec{B} \cdot (\vec{\nabla} \times \vec{A}) - \vec{A} \cdot (\vec{\nabla} \times \vec{B})$$

$$(7) \vec{\nabla} \times (f\vec{A}) = f(\vec{\nabla} \times \vec{A}) - \vec{A} \times (\vec{\nabla}f)$$

$$(8) \vec{\nabla} \times (\vec{A} \times \vec{B}) = (\vec{B} \cdot \vec{\nabla})\vec{A} - (\vec{A} \cdot \vec{\nabla})\vec{B} + \vec{A}(\vec{\nabla} \cdot \vec{B}) - \vec{B}(\vec{\nabla} \cdot \vec{A})$$

### Second Derivatives

$$(9) \vec{\nabla} \cdot (\vec{\nabla} \times \vec{A}) = 0$$

$$(10) \vec{\nabla} \times (\vec{\nabla}f) = 0$$

$$(11) \vec{\nabla} \times (\vec{\nabla} \times \vec{A}) = \vec{\nabla}(\vec{\nabla} \cdot \vec{A}) - \nabla^2 \vec{A}$$

(Fundamental theorems are on the back side)