



Electromagnetic Field Theory 1

(fundamental relations and definitions)

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Fundamental Question of Classical Electrodynamics

A specified distribution of elementary charges is in state of arbitrary (but known) motion. At certain time we pick one of them and ask what is the force acting on it.

Rather difficult question – will not be fully answered



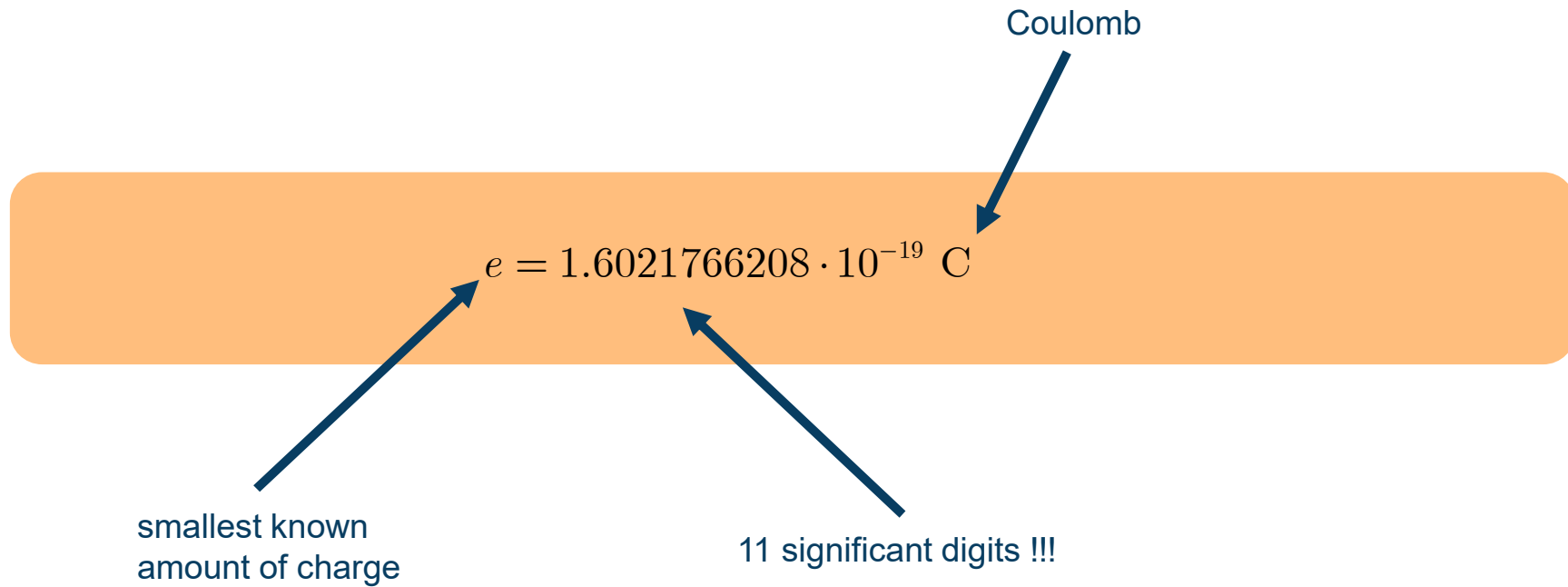
Elementary Charge

$e = 1.6021766208 \cdot 10^{-19} \text{ C}$

Coulomb

smallest known amount of charge

11 significant digits !!!



As far as we known, all charges in nature have values $\pm Ne, N \in \mathbb{Z}$



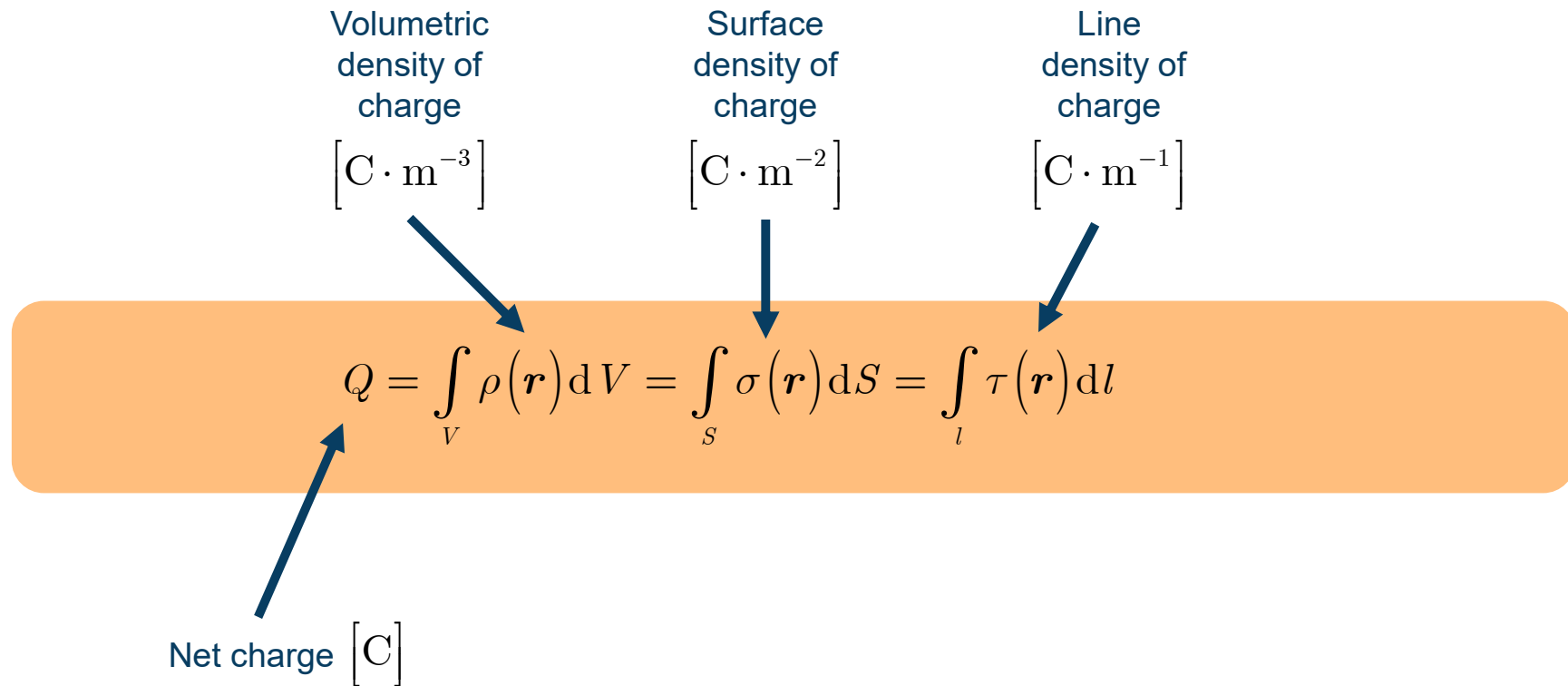
Charge conservation

Amount of charge is conserved in every frame (even non-inertial).

Neutrality of atoms has been verified to 20 digits



Continuous approximation of charge distribution



Continuous approximation allows for using powerful mathematics



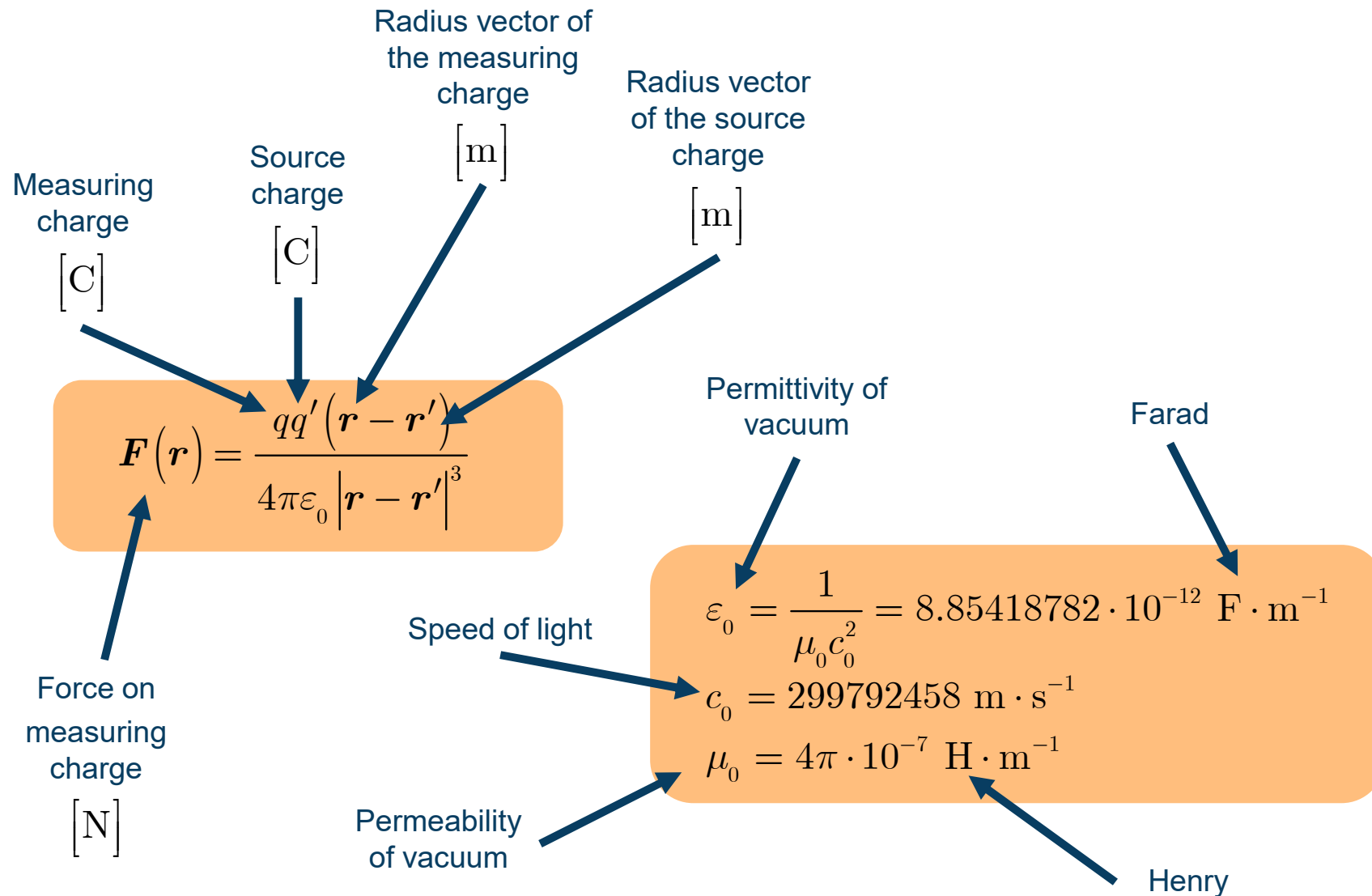
Fundamental Question of Electrostatics

There exist a specified distribution of static elementary charges. We pick one of them and ask what is the force acting on it.

This will be answered in full details



Coulomb('s) Law



Coulomb('s) Law + Superposition Principle

$$\mathbf{F}(\mathbf{r}) = \frac{q}{4\pi\epsilon_0} \sum_n \frac{q'_n (\mathbf{r} - \mathbf{r}'_n)}{|\mathbf{r} - \mathbf{r}'_n|^3}$$

Entire electrostatics can be deduced from this formula



Electric Field

$$\mathbf{F}(\mathbf{r}) = q\mathbf{E}(\mathbf{r}) \qquad \mathbf{E}(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \sum_n \frac{q'_n (\mathbf{r} - \mathbf{r}'_n)}{|\mathbf{r} - \mathbf{r}'_n|^3}$$

Intensity of
electric field
 $[\text{V} \cdot \text{m}^{-1}]$

Force is represented by field – entity generated by charges and permeating the space

Continuous Distribution of Charge

$$\mathbf{E}(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \sum_n \frac{q'_n (\mathbf{r} - \mathbf{r}'_n)}{|\mathbf{r} - \mathbf{r}'_n|^3} \quad \longrightarrow \quad \mathbf{E}(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \int_{V'} \frac{\rho(\mathbf{r}') (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV'$$

Continuous description of charge allows for using powerful mathematics

Continuous Description of a Point Charge

Dirac's delta
"function"

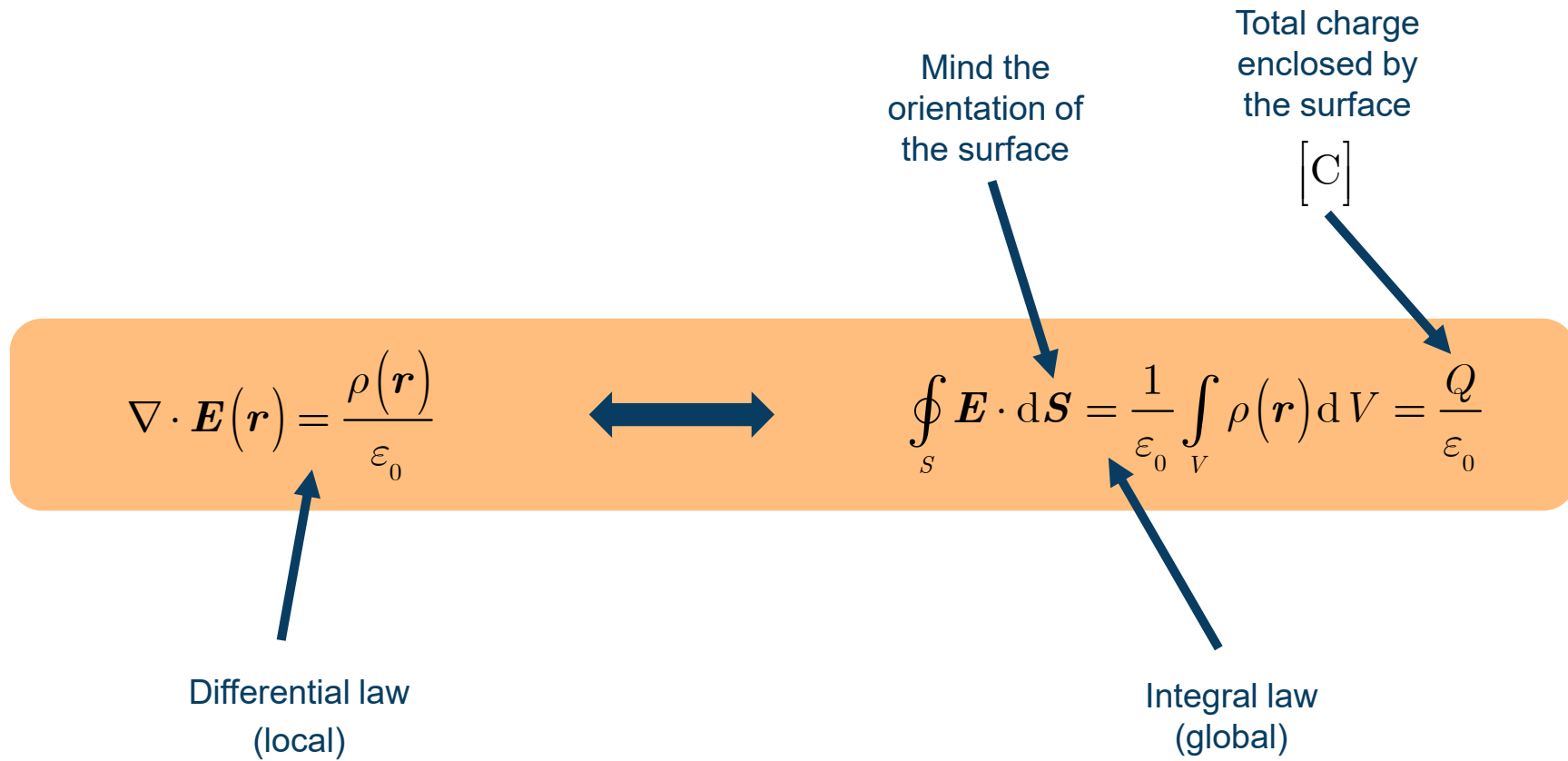
Defining property of
Dirac's delta "function"

$$\rho(\mathbf{r}) = \sum_n q_n \delta(\mathbf{r} - \mathbf{r}_n)$$

$$\mathbf{F}(\mathbf{r}_n) = \int_V \mathbf{F}(\mathbf{r}) \delta(\mathbf{r} - \mathbf{r}_n) dV$$



Gauss(') Law



Rotation of Electric Field



Various Views on Electrostatics

Integral laws of electrostatics



Differential laws of electrostatics



Coulomb's law



$$\oint_S \mathbf{E} \cdot d\mathbf{S} = \frac{Q}{\epsilon_0}$$

$$\oint_l \mathbf{E} \cdot d\mathbf{l} = 0$$



$$\nabla \cdot \mathbf{E}(\mathbf{r}) = \frac{\rho(\mathbf{r})}{\epsilon_0}$$

$$\nabla \times \mathbf{E} = 0$$



$$\mathbf{E}(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \int_{V'} \frac{\rho(\mathbf{r}')(\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV'$$

The physics content is the same, the formalism is different.



Electric potential

Defined up to arbitrary constant

Electric potential

$$\nabla \times \mathbf{E} = 0 \quad \Rightarrow \quad \mathbf{E}(\mathbf{r}) = -\nabla \varphi(\mathbf{r}) \quad \Rightarrow \quad \varphi(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \int_{V'} \frac{\rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} dV' + K$$

Scalar description of electrostatic field

Voltage

Potential difference is a unique number

Voltage [V]

Work necessary to take charge q from point A to point B

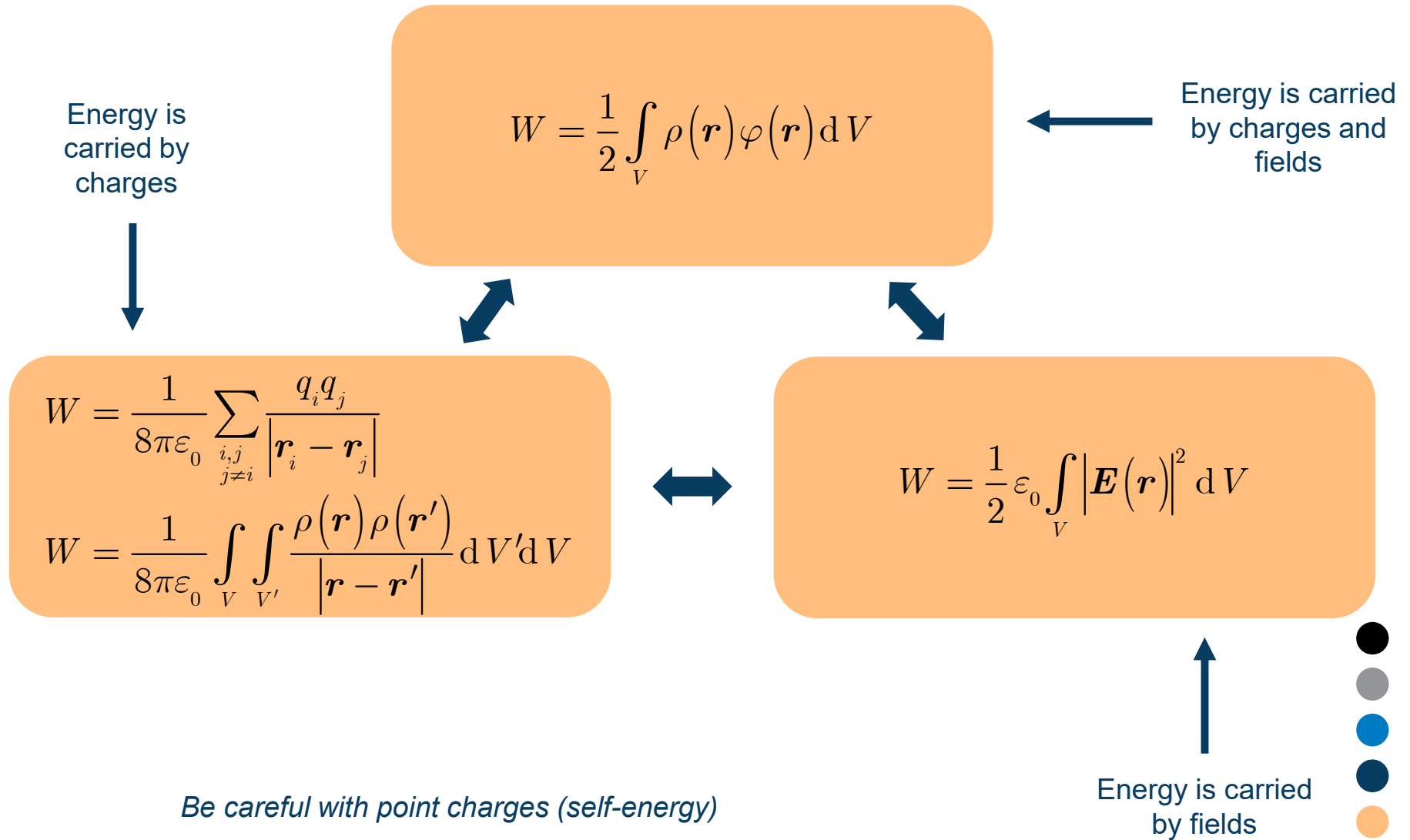
$$-\int_A^B \mathbf{E} \cdot d\mathbf{l} = \varphi(B) - \varphi(A) = U$$

$$W = -\int_A^B \mathbf{F} \cdot d\mathbf{l} = qU$$

Voltage represents connection of abstract field theory with experiments



Electrostatic Energy



Electrostatic Energy vs Force

Energy of a system of point charges



Coulomb's law



$$W = \frac{1}{8\pi\epsilon_0} \sum_{\substack{i,j \\ j \neq i}} \frac{q_i q_j}{|\mathbf{r}_i - \mathbf{r}_j|}$$



$$\mathbf{F}(\mathbf{r}_\xi) = -\nabla_\xi W = \frac{q_\xi}{4\pi\epsilon_0} \sum_{\substack{j \\ j \neq \xi}} q_j \frac{(\mathbf{r}_\xi - \mathbf{r}_j)}{|\mathbf{r}_\xi - \mathbf{r}_j|^3}$$

Electrostatic forces are always acting so to minimize energy of the system



Electric Stress Tensor

Total electric force acting in a volume



Stress tensor



$$\mathbf{F} = \int_V \rho(\mathbf{r}) \mathbf{E}(\mathbf{r}) dV = \varepsilon_0 \oint_S \overline{\overline{\mathbf{T}}} \cdot d\mathbf{S}$$



$$\overline{\overline{\mathbf{T}}} = \mathbf{E}\mathbf{E} - \frac{1}{2} \overline{\overline{\mathbf{I}}} |\mathbf{E}|^2$$

All the information on the volumetric Coulomb's force is contained at the boundary



Ideal Conductor

Ideal conductor contains unlimited amount of free charges which under action of external electric field rearrange so as to annihilate electric field inside the conductor.

In 3D, the free charge always resides on the external bounding surface of the conductor.

In 1D and 2D
it is not so

Generally free charges in conductors move so as to minimize the energy



Boundary Conditions on Ideal Conductor

- Inside conductor

- $\mathbf{E}(\mathbf{r}) = 0 \Leftrightarrow \varphi(\mathbf{r}) = \text{const.}$

Potential is continuous across the boundary

- Just outside conductor

- $\mathbf{n}(\mathbf{r}) \times \mathbf{E}(\mathbf{r}) = 0 \Leftrightarrow \varphi(\mathbf{r}) = \text{const.}$

Surface charge residing on the outer surface of the conductor

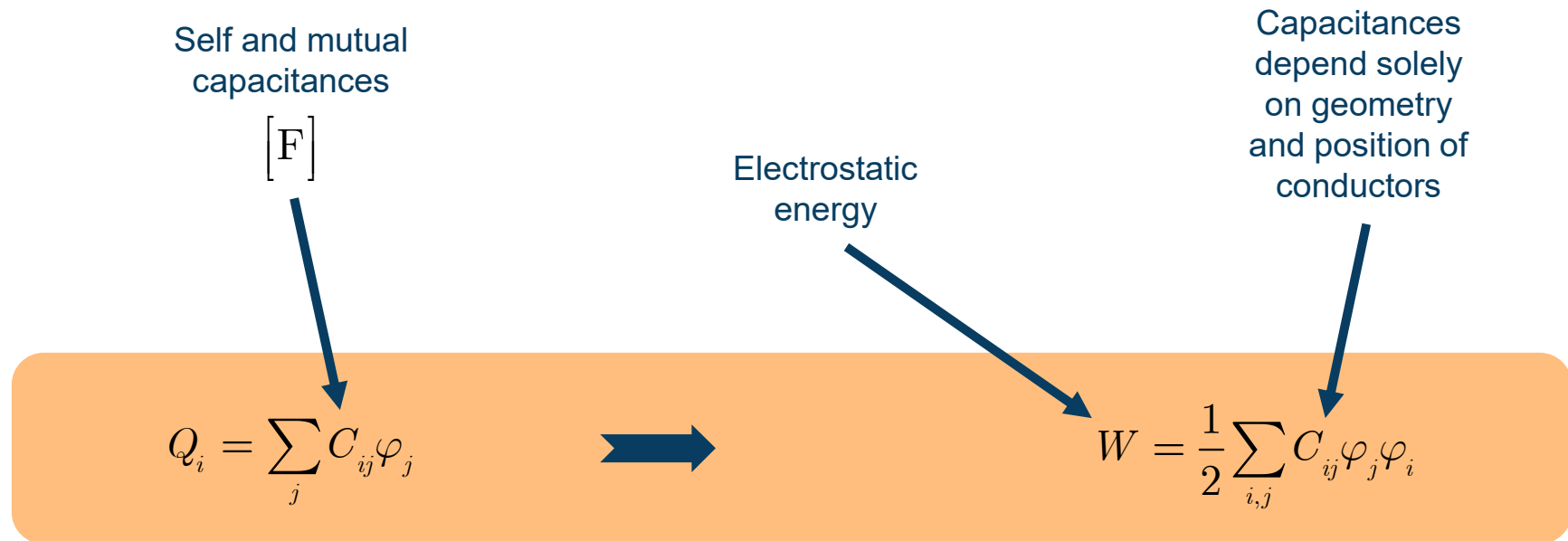
- $\mathbf{n}(\mathbf{r}) \cdot \mathbf{E}(\mathbf{r}) = \frac{\sigma}{\epsilon_0} \Leftrightarrow \frac{\partial \varphi(\mathbf{r})}{\partial n} = -\frac{\sigma}{\epsilon_0}$

Outward normal to the conductor

Normal derivative



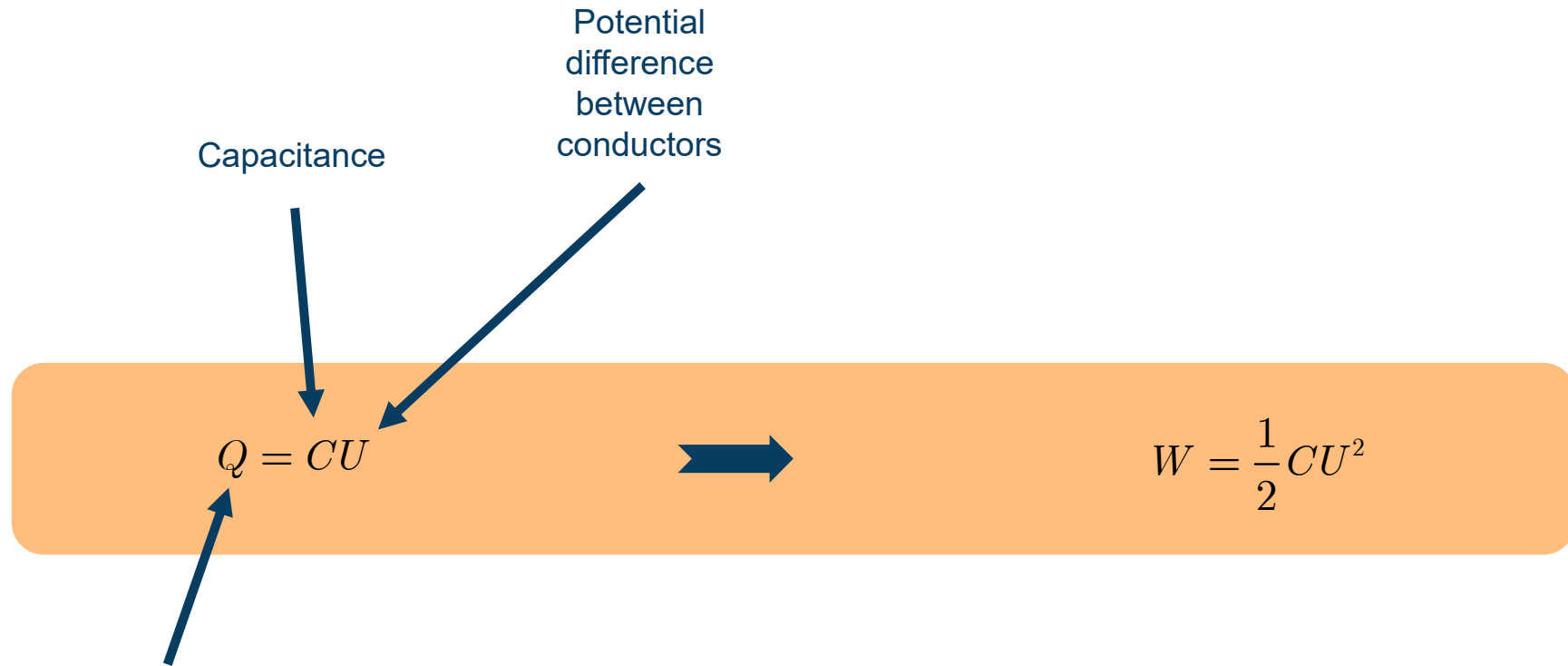
Capacitance of a System of N conductors



Electrostatic system is fully characterized by capacitances (we know the energy)



Capacitance of a System of two conductors



Poisson('s) equation

$$\Delta\varphi(\mathbf{r}) = -\frac{\rho(\mathbf{r})}{\varepsilon_0}$$

The solution to Poisson's equation is unique in a given volume once the potential is known on its bounding surface and the charge density is known through out the volume.



Laplace('s) equation

$$\Delta\varphi(\mathbf{r}) = 0$$

The solution to Laplace's equation is unique in a given volume once the potential is known on its bounding surface.



Mean Value Theorem

Center of the sphere

Only for spheres containing no charge

$$\varphi(\mathbf{r}_{\text{center}}) = \frac{1}{4\pi R^2} \oint_{\text{sphere}} \varphi(\mathbf{r}) dS$$

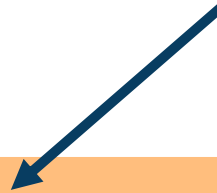
Radius of the sphere

The solution to Laplace's equation possesses neither maxima nor minima inside the solved volume.



Earnshaw('s) Theorem

Consequence of
mean value theorem



A charged particle cannot be held in stable equilibrium by electrostatic forces alone.

Mind that the solution to Laplace's equation posses neither maxima nor minima inside the solved volume. This means that charged particle will always travel towards the boundary.



Image Method

When solving field generated by charges in the presence of conductors, it is sometimes possible to remove the conductor and mimic its boundary conditions by adding extra charges to the exterior of the solution volume. The unicity theorem claims that this is a correct solution.

Image method always works with planes and spheres.



Separation of Variables

Constants
determined by
boundary conditions

$$\Delta\varphi(\mathbf{r}) = 0 \quad \Rightarrow \quad \varphi_{ijk}(\mathbf{r}) = X_i(x)Y_j(y)Z_k(z) \quad \Rightarrow \quad \varphi(\mathbf{r}) = \sum_{ijk} C_{ijk} \varphi_{ijk}(\mathbf{r})$$

Semi-analytical method for canonical problems



Finite Differences

$$\varphi(x+h, y, z) \rightarrow \varphi_{(i+1)jk}$$

$$\Delta\varphi(\mathbf{r}) \approx \frac{\varphi_{(i+1)jk} - 2\varphi_{ijk} + \varphi_{(i-1)jk}}{h^2} + \frac{\varphi_{i(j+1)k} - 2\varphi_{ijk} + \varphi_{i(j-1)k}}{h^2} + \frac{\varphi_{ij(k+1)} - 2\varphi_{ijk} + \varphi_{ij(k-1)}}{h^2}$$

$$\Delta\varphi(\mathbf{r}) = 0 \quad \Rightarrow \quad \varphi_{ijk} = \frac{\varphi_{(i+1)jk} + \varphi_{(i-1)jk} + \varphi_{i(j+1)k} + \varphi_{i(j-1)k} + \varphi_{ij(k+1)} + \varphi_{ij(k-1)}}{6}$$

Approximation by a system of linear algebraic equations

Mind the mean value theorem



Powerful numerical method for closed problems

Method of Moments

Assumed to be known in volume where the charge resides

Distribution of charge is unknown

Simple functions for which the potential integral can be easily evaluated

$$\varphi(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \int_{V'} \frac{\rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} dV'$$

$$\rho(\mathbf{r}) \approx \sum_n \alpha_n \rho_n(\mathbf{r})$$

$$\int_V \rho_m(\mathbf{r}) \varphi(\mathbf{r}) dV = \sum_n \alpha_n \frac{1}{4\pi\epsilon_0} \int_V \int_{V'} \frac{\rho_m(\mathbf{r}) \rho_n(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} dV' dV$$

Known

Approximation by a system of linear algebraic equations

Known

Powerful numerical method for open problems



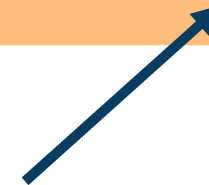
Dielectrics

- Material in which charges cannot move freely
- Charges are forming clusters (atoms, molecules)
- Under influence of electric field the clusters change shape or rotate
- Electric field induces electric dipoles with density $P(r)$ $[C \cdot m^{-2}]$

Clusters are electrically neutral



Number of dipoles in unitary volume



Electric Field of a Dipole

Two opposite charges
very close to each other

$$|\mathbf{r} - \mathbf{r}_{\text{center}}| \gg |\mathbf{r}_1 - \mathbf{r}_2|$$

$$\varphi(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \frac{q}{|\mathbf{r} - \mathbf{r}_1|} - \frac{1}{4\pi\epsilon_0} \frac{q}{|\mathbf{r} - \mathbf{r}_2|} \approx \frac{1}{4\pi\epsilon_0} \frac{\mathbf{p} \cdot (\mathbf{r} - \mathbf{r}_{\text{center}})}{|\mathbf{r} - \mathbf{r}_{\text{center}}|^3}$$

$$\mathbf{p} = q(\mathbf{r}_1 - \mathbf{r}_2) = \int_V \mathbf{r} \rho(\mathbf{r}) dV$$

Electric dipole
moment
[C · m]

Formula for two
opposite charges

General formula



Field Produced by Polarized Matter

$$\varphi(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \int_{V'} \frac{\mathbf{P}(\mathbf{r}') \cdot (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV' = \frac{1}{4\pi\epsilon_0} \oint_{S'} \frac{\mathbf{P}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} \cdot d\mathbf{S}' - \frac{1}{4\pi\epsilon_0} \int_{V'} \frac{\nabla' \cdot \mathbf{P}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} dV'$$

Only apply at infinitely sharp boundary (unrealistic)

Potential of volumetric charge density

This formula holds very well outside the matter and, curiously, it also well approximates the field inside

Electric Displacement

Electric displacement $[\text{C} \cdot \text{m}^{-2}]$

$$\nabla \cdot \mathbf{D}(\mathbf{r}) = \rho(\mathbf{r})$$

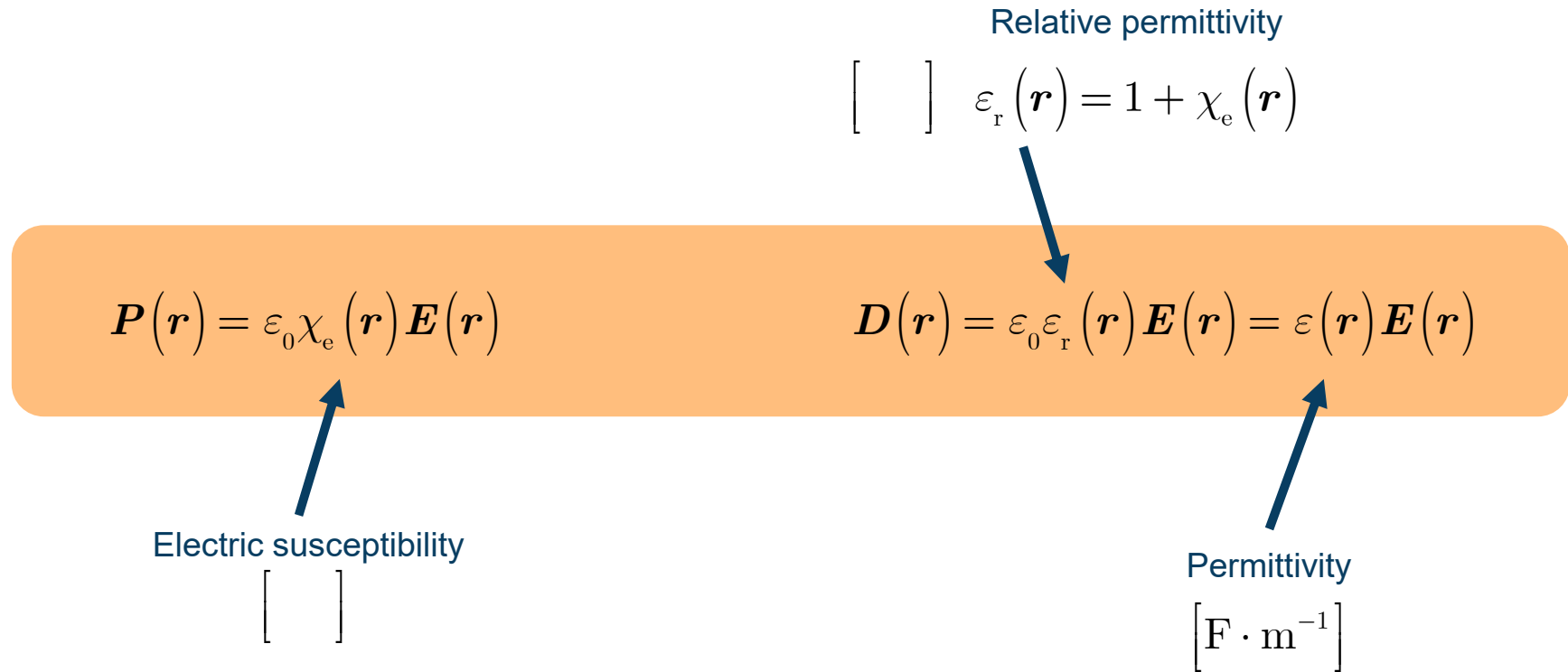
$$\mathbf{D}(\mathbf{r}) = \epsilon_0 \mathbf{E}(\mathbf{r}) + \mathbf{P}(\mathbf{r})$$

$$\oint_S \mathbf{D} \cdot d\mathbf{S} = \int_V \rho(\mathbf{r}) dV = Q$$

Only free charge
(compare to divergence
of electric field)



Linear Isotropic Dielectrics



All the complicated structure of matter reduces to a simple scalar quantity



Fields in Presence of Dielectrics 1/2

Analogy with electric field in vacuum can only be used when entire space is homogeneously filled with dielectric.

$$\nabla \times \mathbf{D}(\mathbf{r}) = \nabla \times [\varepsilon(\mathbf{r}) \mathbf{E}(\mathbf{r})] \neq 0$$

Inequality is due to boundaries

Analogy with vacuum can only be used when space is homogeneously filled with dielectric



Fields in Presence of Dielectrics 2/2

$$\nabla \times \mathbf{E}(\mathbf{r}) = 0 \Leftrightarrow \mathbf{E}(\mathbf{r}) = -\nabla\varphi(\mathbf{r}) \quad \Rightarrow \quad \nabla \cdot [\varepsilon(\mathbf{r})\nabla\varphi(\mathbf{r})] = -\rho(\mathbf{r})$$

$$\Delta\varphi(\mathbf{r}) = -\frac{\rho(\mathbf{r})}{\varepsilon}$$

Not a function of
coordinates

Poisson's equation holds only when permittivity does not depend on coordinates

Dielectric Boundaries

$$\mathbf{n}(\mathbf{r}) \times [\mathbf{E}_1(\mathbf{r}) - \mathbf{E}_2(\mathbf{r})] = 0 \quad \Leftrightarrow \quad \varphi_1(\mathbf{r}) - \varphi_2(\mathbf{r}) = 0$$

$$\mathbf{n}(\mathbf{r}) \cdot [\varepsilon_1 \mathbf{E}_1(\mathbf{r}) - \varepsilon_2 \mathbf{E}_2(\mathbf{r})] = \sigma \quad \Leftrightarrow \quad \varepsilon_1 \frac{\partial \varphi_1(\mathbf{r})}{\partial n} - \varepsilon_2 \frac{\partial \varphi_2(\mathbf{r})}{\partial n} = -\sigma$$

Normal
pointing to
region (1)

Both conditions are needed for unique solution

Electrostatic Energy in Dielectrics

$$W = \frac{1}{2} \varepsilon_0 \int_V |\mathbf{E}(\mathbf{r})|^2 dV$$



$$W = \frac{1}{2} \int_V \mathbf{E}(\mathbf{r}) \cdot \mathbf{D}(\mathbf{r}) dV$$



Forces on Dielectrics

This only holds when charge is held constant

$$W = \frac{1}{2} C U^2 = \frac{1}{2} \frac{Q^2}{C}$$

$$W = \frac{1}{2} \int_V \mathbf{E}(\mathbf{r}) \cdot \mathbf{D}(\mathbf{r}) dV$$



$$\mathbf{F}(\mathbf{r}_\xi) = -\nabla_\xi W$$



Electric Current

Current density
 $[A \cdot m^{-2}]$

Charge
 $[C]$

Velocity of charge
 $[m \cdot s^{-1}]$

$$\mathbf{J}(\mathbf{r}, t) = \sum_{k=1}^N q_k \delta(\mathbf{r} - \mathbf{r}_k(t)) \mathbf{v}_k(t)$$

Volumetric density represented by Dirac delta

$[m^{-3}]$

Charges in motion are represented by current density



Local Charge Conservation


$$\nabla \cdot \mathbf{J}(\mathbf{r}, t) = -\frac{\partial}{\partial t} \sum_{k=1}^N q_k \delta(\mathbf{r} - \mathbf{r}_k(t)) = -\frac{\partial \rho(\mathbf{r}, t)}{\partial t}$$

Charge is conserved locally at every space-time point



Global Charge Conservation

When charge leaves a given volume, it is always accompanied by a current through the bounding envelope


$$\oint_S \mathbf{J}(\mathbf{r}, t) \cdot d\mathbf{S} = -\frac{\partial Q(t)}{\partial t}$$

Charge can neither be created nor destroyed. It can only be displaced.



Stationary Current

When charge enters a volume, another must leave it without any delay



$$\nabla \cdot \mathbf{J}(\mathbf{r}) = 0$$



$$\oint_S \mathbf{J}(\mathbf{r}) \cdot d\mathbf{S} = 0$$

There is no charge accumulation in stationary flow



Ohm('s) Law

Conductivity

$$[\text{S} \cdot \text{m}^{-1}]$$



$$\mathbf{J}(\mathbf{r}) = \sigma(\mathbf{r}) \mathbf{E}(\mathbf{r})$$

This simple linear relation holds for enormous interval of electric field strengths



Electromotive Force

Stationary flow of charges cannot be caused by electrostatic field. The motion forces are non-conservative, are called electromotive forces, and are commonly of chemical, magnetic or photoelectric origin.

$$\oint_l \mathbf{E}(\mathbf{r}) \cdot d\mathbf{l} \neq 0$$

For curves passing through sources of electromotive force

$$\oint_l \mathbf{E}(\mathbf{r}) \cdot d\mathbf{l} = 0$$

For curves not crossing sources of electromotive force



Boundary Conditions for Stationary Current

$$\mathbf{n}(\mathbf{r}) \times [\mathbf{E}_1(\mathbf{r}) - \mathbf{E}_2(\mathbf{r})] = 0 \quad \Leftrightarrow \quad \varphi_1(\mathbf{r}) - \varphi_2(\mathbf{r}) = 0$$

$$\mathbf{n}(\mathbf{r}) \cdot [\varepsilon_1 \mathbf{E}_1(\mathbf{r}) - \varepsilon_2 \mathbf{E}_2(\mathbf{r})] = \sigma \quad \Leftrightarrow \quad \varepsilon_1 \frac{\partial \varphi_1(\mathbf{r})}{\partial n} - \varepsilon_2 \frac{\partial \varphi_2(\mathbf{r})}{\partial n} = -\sigma$$

$$\mathbf{n}(\mathbf{r}) \cdot [\sigma_1 \mathbf{E}_1(\mathbf{r}) - \sigma_2 \mathbf{E}_2(\mathbf{r})] = 0 \quad \Leftrightarrow \quad \sigma_1 \frac{\partial \varphi_1(\mathbf{r})}{\partial n} - \sigma_2 \frac{\partial \varphi_2(\mathbf{r})}{\partial n} = 0$$

Charge conservation forces the continuity of current across the boundary

Electric Current

Current
[A]

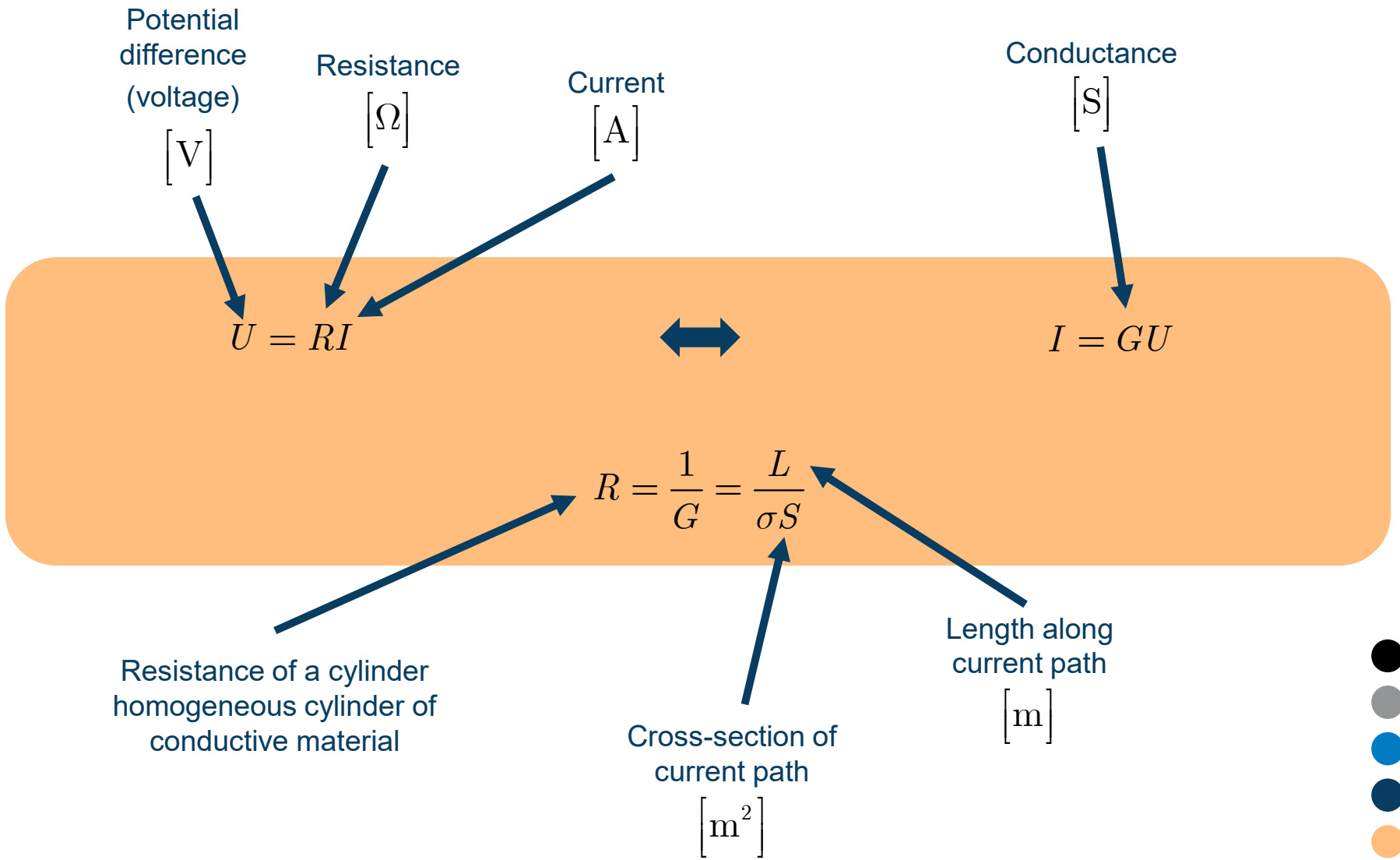
$$I = \int_S \mathbf{J}(\mathbf{r}) \cdot d\mathbf{S}$$

Cross-section of
current path
[m²]

Existence of high contrast in conductivity between conductors and dielectrics allows for well defined current paths.



Resistance (Conductance)



Resistive Circuits and Kirchhoff('s) Laws

In a loop

$$\sum_i U_i = U_{\text{electromotive}}$$

On a resistor

$$U_i = R_i I_i$$

At a junction

$$\sum_i I_i = 0$$

Kirchhoff's laws are a consequence of electrostatics and law's of stationary current flow



Joule('s) Heat

Power lost via
conduction

[W]

Power lost on
resistor

[W]

$$P = \int_V \mathbf{E}(\mathbf{r}) \cdot \mathbf{J}(\mathbf{r}) dV = \int_V \sigma(\mathbf{r}) |\mathbf{E}(\mathbf{r})|^2 dV$$



$$P = UI = RI^2 = \frac{U^2}{R}$$

Electric field within conducting material produce heat

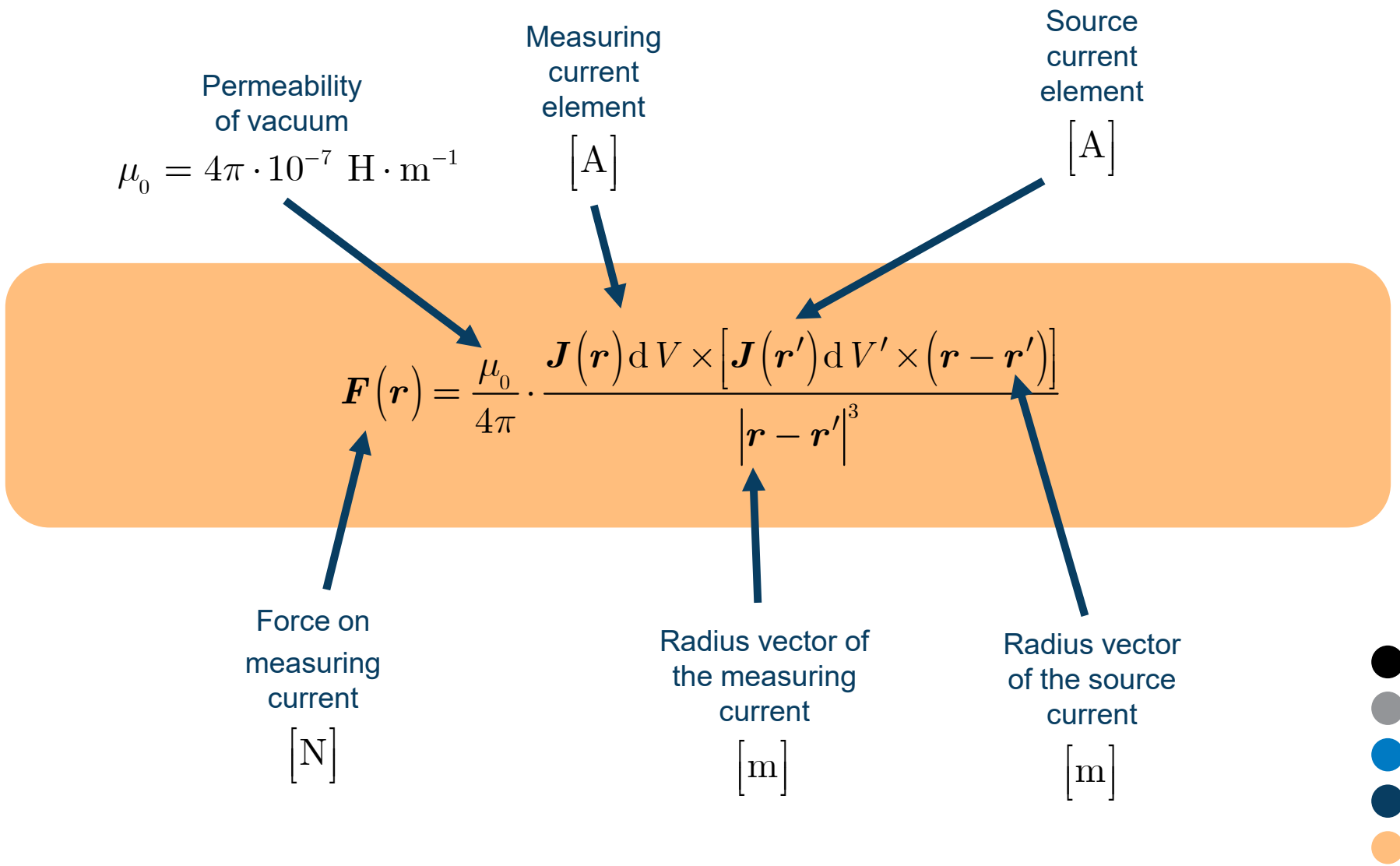


Fundamental Question of Magnetostatics

There exist a specified distribution of stationary current. We pick a differential volume of it and ask what is the force acting on it.



Biot-Savart('s) Law



Biot-Savart('s) Law + Superposition Principle

$$\mathbf{F}(\mathbf{r}) = \mathbf{J}(\mathbf{r}) dV \times \frac{\mu_0}{4\pi} \int_{V'} \frac{\mathbf{J}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV'$$

Entire magnetostatics can be deduced from this formula

Magnetic Field

$$\mathbf{F}(\mathbf{r}) = \mathbf{J}(\mathbf{r}) dV \times \mathbf{B}(\mathbf{r})$$



$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int_{V'} \frac{\mathbf{J}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV'$$

Magnetic field
(Magnetic induction)
[T]



Divergence of Magnetic Field

$$\nabla \cdot \mathbf{B}(\mathbf{r}) = 0$$



$$\oint_S \mathbf{B}(\mathbf{r}) \cdot d\mathbf{S} = 0$$

There are no point sources of magnetostatic field



Curl of Magnetic Field – Ampere('s) Law

$$\nabla \times \mathbf{B}(\mathbf{r}) = \mu_0 \mathbf{J}(\mathbf{r})$$



$$\oint_l \mathbf{B}(\mathbf{r}) \cdot d\mathbf{l} = \mu_0 I$$

Total current
captured within
the curve

[A]



Magnetic Vector Potential

Magnetic vector potential

Defined up to arbitrary scalar function

$$\nabla \cdot \mathbf{B} = 0 \implies \mathbf{B}(\mathbf{r}) = \nabla \times \mathbf{A}(\mathbf{r}) \implies \mathbf{A}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int_{V'} \frac{\mathbf{J}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} dV' + \nabla\psi(\mathbf{r})$$

Reduced description of magnetostatic field

Poisson('s) equation

$$\Delta \mathbf{A}(\mathbf{r}) = -\mu_0 \mathbf{J}(\mathbf{r})$$

The solution to Poisson's equation is unique in a given volume once the potential is known on its bounding surface and the current density is known through out the volume.



Boundary Conditions

Surface current on the boundary

$$\mathbf{n}(\mathbf{r}) \times [\mathbf{B}_1(\mathbf{r}) - \mathbf{B}_2(\mathbf{r})] = \mu_0 \mathbf{K}(\mathbf{r})$$
$$\mathbf{n}(\mathbf{r}) \cdot [\mathbf{B}_1(\mathbf{r}) - \mathbf{B}_2(\mathbf{r})] = 0$$
$$\mathbf{A}_1(\mathbf{r}) - \mathbf{A}_2(\mathbf{r}) = 0$$

Normal pointing to region (1)



Magnetostatic Energy

$$W = \frac{1}{2} \int_V \mathbf{A}(\mathbf{r}) \cdot \mathbf{J}(\mathbf{r}) dV \quad \longleftrightarrow \quad W = \frac{1}{2\mu_0} \int_V |\mathbf{B}(\mathbf{r})|^2 dV$$

For now it is just a formula that works – it must be derived with the help of time varying fields



Magnetostatic Energy – Current Circuits

$$M_{ij} = M_{ji} = \frac{\mu_0}{4\pi I_i I_j} \int_{V_j} \int_{V_i'} \frac{\mathbf{J}_j(\mathbf{r}_j) \cdot \mathbf{J}_i(\mathbf{r}_i')}{|\mathbf{r}_j - \mathbf{r}_i'|} dV_i' dV_j$$

Mutual-Inductance [H]

$$W = \frac{1}{2} \sum_{i=1}^N L_i I_i^2 + \frac{1}{2} \sum_{i \neq j} M_{ij} I_i I_j$$

Self-Inductance [H]

$$L_i = \frac{\mu_0}{4\pi I_i^2} \int_{V_i} \int_{V_i'} \frac{\mathbf{J}_i(\mathbf{r}_i) \cdot \mathbf{J}_i(\mathbf{r}_i')}{|\mathbf{r}_i - \mathbf{r}_i'|} dV_i' dV_i$$

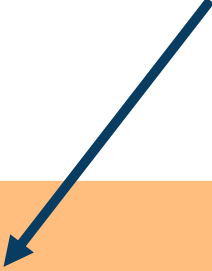


Mutual Inductance – Thin Current Loop

$$\Phi_{ji} = \int_{S_j} \mathbf{B}_i(\mathbf{r}_j) \cdot d\mathbf{S}_j$$

Magnetic flux induced by i -th current through j -th current

[Wb]


$$M_{ij} = \frac{\Phi_{ji}}{I_i}$$



Magnetic Materials

- Material response is due to magnetic dipole moments
- Magnetic moment comes from spin or orbital motion of an electron
- Magnetic field tends to align magnetic moments
- Magnetic field induces magnetic dipoles with density $M(\mathbf{r})$ $[\text{A} \cdot \text{m}^{-1}]$

Number of dipoles
in unitary volume



Magnetic Field of a Dipole

Dipole is assumed at the origin

$r \neq 0$

$$\mathbf{A}(\mathbf{r}) = \frac{\mu_0}{4\pi} \cdot \frac{\mathbf{m} \times \mathbf{r}}{r^3}$$



$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \left[\frac{3\mathbf{r}(\mathbf{r} \cdot \mathbf{m})}{r^5} - \frac{\mathbf{m}}{r^3} \right]$$

$$\mathbf{m} = \frac{1}{2} \int_V \mathbf{r} \times \mathbf{J}(\mathbf{r}) dV$$

Magnetic dipole moment

$$[\text{A} \cdot \text{m}^2]$$

Magnetic dipole approximates infinitesimally small current loop



Field Produced by Magnetized Matter

$$\mathbf{A}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int_{V'} \frac{\mathbf{M}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV' = \frac{\mu_0}{4\pi} \oint_{S'} \frac{\mathbf{M}(\mathbf{r}') \times d\mathbf{S}'}{|\mathbf{r} - \mathbf{r}'|} + \frac{\mu_0}{4\pi} \int_{V'} \frac{\nabla' \times \mathbf{M}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} dV'$$

Only applies at infinitely sharp boundary (unrealistic)

Potential of volumetric current density

This formula holds very well outside the matter and, curiously, it also well approximates the field inside

Magnetic Intensity

Magnetic Intensity $[A \cdot m^{-1}]$

$$\nabla \times \mathbf{H}(\mathbf{r}) = \mathbf{J}(\mathbf{r})$$

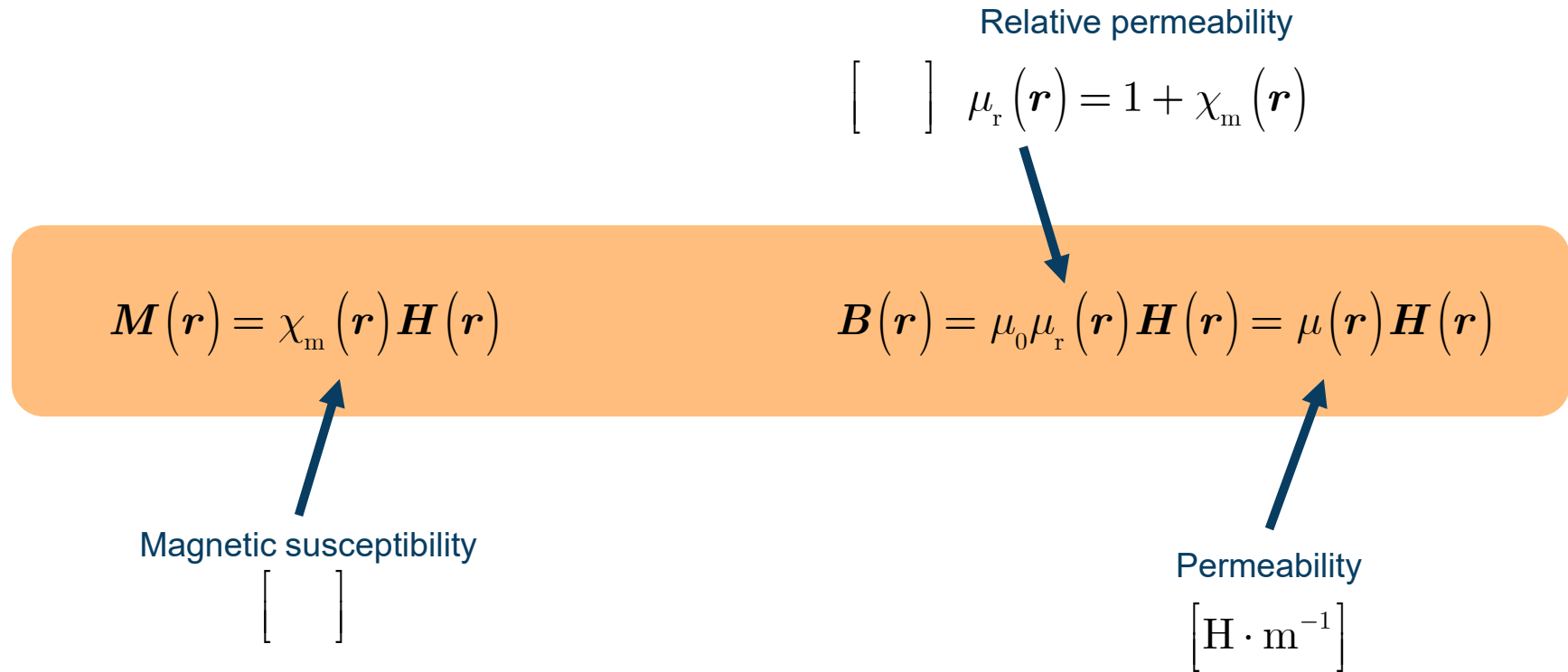
$$\mathbf{B}(\mathbf{r}) = \mu_0 (\mathbf{H}(\mathbf{r}) + \mathbf{M}(\mathbf{r}))$$

$$\oint_l \mathbf{H}(\mathbf{r}) \cdot d\mathbf{l} = I$$

Only free current



Linear Isotropic Magnetic Materials



All the complicated structure of matter reduces to a simple scalar quantity



Fields in Presence of Magnetic Material

$$\nabla \cdot \mathbf{B}(\mathbf{r}) = 0 \Leftrightarrow \mathbf{B}(\mathbf{r}) = \nabla \times \mathbf{A}(\mathbf{r}) \quad \Rightarrow \quad \nabla \times \left[\frac{1}{\mu(\mathbf{r})} \nabla \times \mathbf{A}(\mathbf{r}) \right] = \mathbf{J}(\mathbf{r})$$

$$\Delta \mathbf{A}(\mathbf{r}) = -\mu \mathbf{J}(\mathbf{r})$$

$$\nabla \cdot \mathbf{A}(\mathbf{r}) = 0$$

Coulomb('s) gauge

Not a function of
coordinates

Poisson's equation holds only when permittivity does not depend on coordinates



Magnetic Material Boundaries

$$\mathbf{n}(\mathbf{r}) \times [\mathbf{H}_1(\mathbf{r}) - \mathbf{H}_2(\mathbf{r})] = \mathbf{K}(\mathbf{r})$$

$$\mathbf{n}(\mathbf{r}) \cdot [\mu_1 \mathbf{H}_1(\mathbf{r}) - \mu_2 \mathbf{H}_2(\mathbf{r})] = 0$$

Normal
pointing to
region (1)

Both conditions are needed for unique solution



Magnetostatic Energy in Magnetic Material

$$W = \frac{1}{2\mu_0} \int_V |\mathbf{B}(\mathbf{r})|^2 dV$$



$$W = \frac{1}{2} \int_V \mathbf{H}(\mathbf{r}) \cdot \mathbf{B}(\mathbf{r}) dV$$



Magnetic Materials

- **Paramagnetic** – small positive susceptibility (small attraction – **linear**)
- **Diamagnetic** – small negative susceptibility (small repulsion – **linear**)
- **Ferromagnetic** – “*large positive susceptibility*” (large attraction – **nonlinear**)



Ferromagnetic Materials

- Spins are ordered within domains
- Magnetization is a non-linear function of field intensity
- Magnetization curve – Hysteresis, Remanence
- Susceptibility can only be defined as local approximation
- Above Curie('s) temperature ferromagnetism disappears

Exact calculations are very difficult – use simplified models (soft material, permanent magnet)



Faraday('s) Law

Minus sign is called
Lenz('s) law

$-\frac{\partial\Phi}{\partial t}$ Time variation of
magnetic flux

$$\oint_l \mathbf{E}(\mathbf{r}, t) \cdot d\mathbf{l} = -\frac{\partial}{\partial t} \int_s \mathbf{B}(\mathbf{r}, t) \cdot d\mathbf{S} \quad \longleftrightarrow \quad \nabla \times \mathbf{E}(\mathbf{r}, t) = -\frac{\partial \mathbf{B}(\mathbf{r}, t)}{\partial t}$$

Time variation in magnetic field produces electric field that tries to counter the change in magnetic flux (electromotive force)

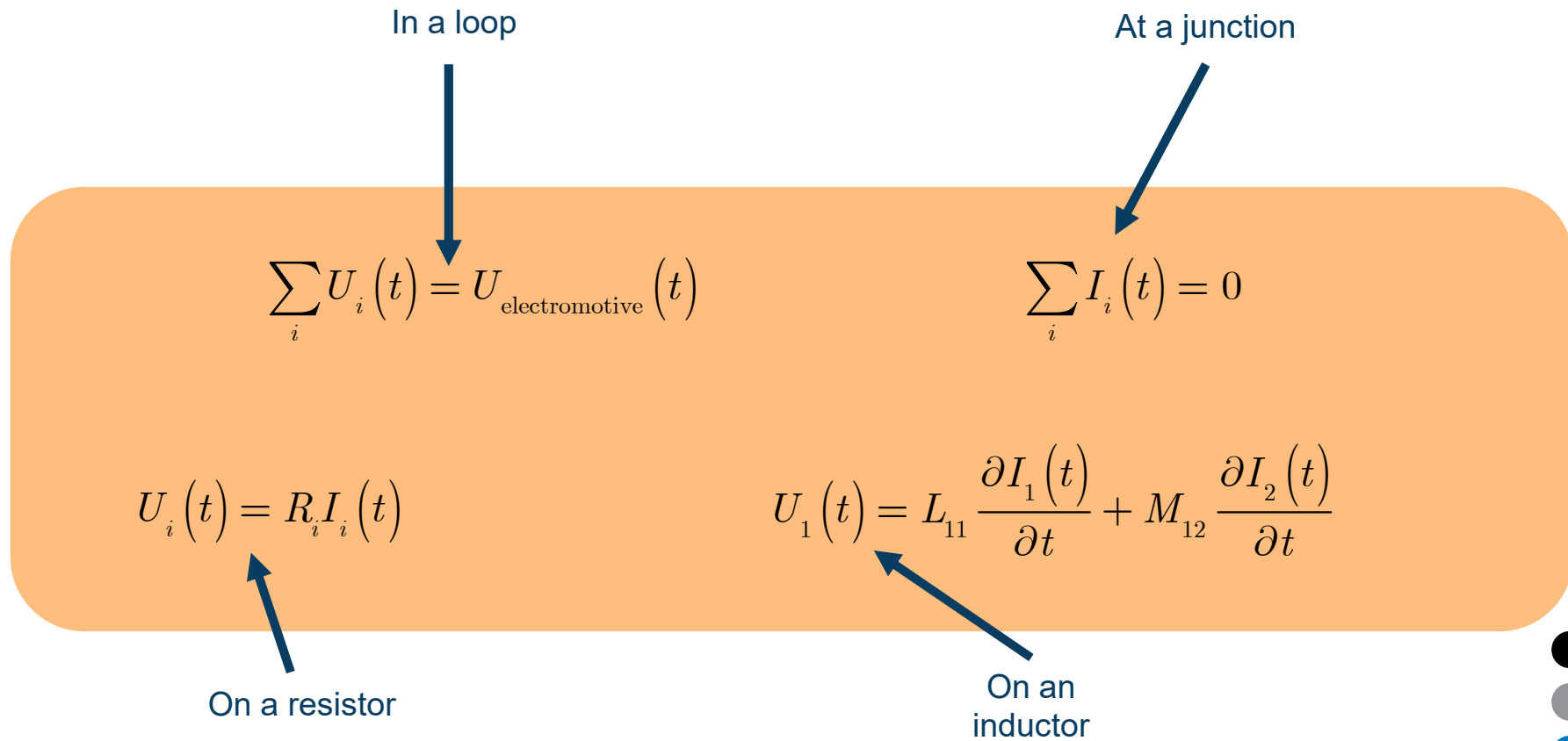


Lenz('s) Law

The current created by time variation of magnetic flux is directed so as to oppose the flux creating it.



Time Varying RL Circuits



Circuit laws are valid as long as the variations are not too fast



Time Varying Potentials

Potential
calibration

$$\nabla \cdot \mathbf{A}(\mathbf{r}, t) = -\sigma\mu\varphi(\mathbf{r}, t)$$

$$\mathbf{B}(\mathbf{r}, t) = \nabla \times \mathbf{A}(\mathbf{r}, t)$$

$$\mathbf{E}(\mathbf{r}, t) = -\nabla\varphi(\mathbf{r}, t) - \frac{\partial\mathbf{A}(\mathbf{r}, t)}{\partial t}$$

In time varying fields scalar potential becomes redundant



Source and Induced Currents

Those are fixed, not reacting to fields

$$\nabla \times \mathbf{H}(\mathbf{r}, t) = \mathbf{J}_{\text{source}}(\mathbf{r}, t) + \mathbf{J}_{\text{induced}}(\mathbf{r}, t) = \mathbf{J}_{\text{source}}(\mathbf{r}, t) + \sigma \mathbf{E}(\mathbf{r}, t)$$



Diffusion Equation

$$\Delta \mathbf{A}(\mathbf{r}, t) - \sigma \mu \frac{\partial \mathbf{A}(\mathbf{r}, t)}{\partial t} = -\mu \mathbf{J}_{\text{source}}(\mathbf{r}, t)$$

$$\Delta \mathbf{H}(\mathbf{r}, t) - \sigma \mu \frac{\partial \mathbf{H}(\mathbf{r}, t)}{\partial t} = -\nabla \times \mathbf{J}_{\text{source}}(\mathbf{r}, t)$$

$$\Delta \mathbf{E}(\mathbf{r}, t) - \sigma \mu \frac{\partial \mathbf{E}(\mathbf{r}, t)}{\partial t} = \frac{1}{\varepsilon} \nabla \rho_{\text{source}}(\mathbf{r}, t) + \mu \frac{\partial \mathbf{J}_{\text{source}}(\mathbf{r}, t)}{\partial t}$$

Material parameters are assumed independent of coordinates



Maxwell('s)-Lorentz('s) Equations

$$\nabla \times \mathbf{H}(\mathbf{r}, t) = \mathbf{J}(\mathbf{r}, t) + \frac{\partial \mathbf{D}(\mathbf{r}, t)}{\partial t}$$

Equations of motion
for fields

$$\nabla \times \mathbf{E}(\mathbf{r}, t) = -\frac{\partial \mathbf{B}(\mathbf{r}, t)}{\partial t}$$

$$\nabla \cdot \mathbf{B}(\mathbf{r}, t) = 0$$

$$\nabla \cdot \mathbf{D}(\mathbf{r}, t) = \rho(\mathbf{r}, t)$$

Equation of motion
for particles

$$\mathbf{f}(\mathbf{r}, t) = \rho(\mathbf{r}, t) \mathbf{E}(\mathbf{r}, t) + \mathbf{J}(\mathbf{r}, t) \times \mathbf{B}(\mathbf{r}, t)$$

Interaction with materials

$$\begin{aligned} \mathbf{D}(\mathbf{r}, t) &= \varepsilon_0 \mathbf{E}(\mathbf{r}, t) + \mathbf{P}(\mathbf{r}, t) \\ \mathbf{B}(\mathbf{r}, t) &= \mu_0 (\mathbf{H}(\mathbf{r}, t) + \mathbf{M}(\mathbf{r}, t)) \end{aligned}$$

Absolute majority of things happening around you is described by these equations



Boundary Conditions

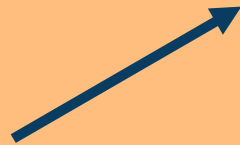
$$\mathbf{n}(\mathbf{r}) \times [\mathbf{E}_1(\mathbf{r}, t) - \mathbf{E}_2(\mathbf{r}, t)] = 0$$

$$\mathbf{n}(\mathbf{r}) \times [\mathbf{H}_1(\mathbf{r}, t) - \mathbf{H}_2(\mathbf{r}, t)] = \mathbf{K}(\mathbf{r}, t)$$

$$\mathbf{n}(\mathbf{r}) \cdot [\mathbf{B}_1(\mathbf{r}, t) - \mathbf{B}_2(\mathbf{r}, t)] = 0$$

$$\mathbf{n}(\mathbf{r}) \cdot [\mathbf{D}_1(\mathbf{r}, t) - \mathbf{D}_2(\mathbf{r}, t)] = \sigma(\mathbf{r}, t)$$

Normal
pointing to
region (1)



Electromagnetic Potentials

Lorentz('s)
calibration

$$\nabla \cdot \mathbf{A}(\mathbf{r}, t) = -\sigma\mu\varphi(\mathbf{r}, t) - \varepsilon\mu \frac{\partial\varphi(\mathbf{r}, t)}{\partial t}$$

$$\mathbf{B}(\mathbf{r}, t) = \nabla \times \mathbf{A}(\mathbf{r}, t)$$

$$\mathbf{E}(\mathbf{r}, t) = -\nabla\varphi(\mathbf{r}, t) - \frac{\partial\mathbf{A}(\mathbf{r}, t)}{\partial t}$$



Wave Equation

$$\Delta \mathbf{A}(\mathbf{r}, t) - \sigma \mu \frac{\partial \mathbf{A}(\mathbf{r}, t)}{\partial t} - \varepsilon \mu \frac{\partial^2 \mathbf{A}(\mathbf{r}, t)}{\partial t^2} = -\mu \mathbf{J}_{\text{source}}(\mathbf{r}, t)$$

Material parameters are assumed independent of coordinates



Poynting('s)-Umov('s) Theorem

Power passing the bounding envelope

Energy storage

$$-\int_V \mathbf{E} \cdot \mathbf{J}_{\text{source}} dV = \oint_S (\mathbf{E} \times \mathbf{H}) \cdot d\mathbf{S} + \int_V \sigma |\mathbf{E}|^2 dV + \frac{1}{2} \frac{\partial}{\partial t} \int_V (\epsilon |\mathbf{E}|^2 + \mu |\mathbf{H}|^2) dV$$

Power supplied by sources


Heat losses

Energy balance in an electromagnetic system



Linear Momentum Carried by Fields

Volume integration considerably change
the meaning of Poynting('s) vector


$$\mathbf{p} = \frac{1}{c_0^2} \int_V (\mathbf{E} \times \mathbf{H}) dV$$

This formula is only valid in vacuum. In material media things are more tricky.



Angular Momentum Carried by Fields

$$\mathbf{L} = \frac{1}{c_0^2} \int_V \mathbf{r} \times (\mathbf{E} \times \mathbf{H}) dV$$

This formula is only valid in vacuum. In material media things are more tricky.



Frequency Domain

$$\mathbf{F}(\mathbf{r}, t) \in \mathbb{R}$$

$$\hat{\mathbf{F}}(\mathbf{r}, \omega) \in \mathbb{C}$$

$$\mathbf{F}(\mathbf{r}, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{\mathbf{F}}(\mathbf{r}, \omega) e^{j\omega t} d\omega$$



$$\hat{\mathbf{F}}(\mathbf{r}, \omega) = \int_{-\infty}^{\infty} \mathbf{F}(\mathbf{r}, t) e^{-j\omega t} dt$$

$$\frac{\partial \mathbf{F}(\mathbf{r}, t)}{\partial t} \leftrightarrow j\omega \hat{\mathbf{F}}(\mathbf{r}, \omega)$$

Time derivatives reduce to algebraic multiplication

$$\frac{\partial \mathbf{F}(\mathbf{r}, t)}{\partial r_\xi} \leftrightarrow \frac{\partial \hat{\mathbf{F}}(\mathbf{r}, \omega)}{\partial r_\xi}$$

Spatial derivatives are untouched

Frequency domain helps us to remove explicit time derivatives



Phasors

$$\hat{\mathbf{F}}(\mathbf{r}, -\omega) = \hat{\mathbf{F}}^*(\mathbf{r}, \omega)$$



$$\mathbf{F}(\mathbf{r}, t) = \frac{1}{\pi} \int_0^{\infty} \text{Re}[\hat{\mathbf{F}}(\mathbf{r}, \omega) e^{j\omega t}] d\omega$$

Reduced frequency domain representation



Maxwell('s) Equations – Frequency Domain

$$\nabla \times \hat{\mathbf{H}}(\mathbf{r}, \omega) = \hat{\mathbf{J}}(\mathbf{r}, \omega) + j\omega\epsilon\hat{\mathbf{E}}(\mathbf{r}, \omega)$$

$$\nabla \times \hat{\mathbf{E}}(\mathbf{r}, \omega) = -j\omega\mu\hat{\mathbf{H}}(\mathbf{r}, \omega)$$

$$\nabla \cdot \hat{\mathbf{H}}(\mathbf{r}, \omega) = 0$$

$$\nabla \cdot \hat{\mathbf{E}}(\mathbf{r}, \omega) = \frac{\hat{\rho}(\mathbf{r}, \omega)}{\epsilon}$$

We assume linearity of material relations



Wave Equation – Frequency Domain

$$\Delta \hat{\mathbf{A}}(\mathbf{r}, \omega) - j\omega\mu(\sigma + j\omega\varepsilon)\hat{\mathbf{A}}(\mathbf{r}, \omega) = -\mu\hat{\mathbf{J}}_{\text{source}}(\mathbf{r}, \omega)$$

Helmholtz('s) equation



Heat Balance in Time-Harmonic Steady State

Valid for general periodic steady state

Cycle mean

$$-\int_V \langle \mathbf{E} \cdot \mathbf{J}_{\text{source}} \rangle dV = \oint_S \langle \mathbf{E} \times \mathbf{H} \rangle \cdot d\mathbf{S} + \int_V \langle \sigma |\mathbf{E}|^2 \rangle dV$$
$$-\frac{1}{2} \int_V \text{Re}[\hat{\mathbf{E}} \cdot \hat{\mathbf{J}}_{\text{source}}^*] dV = \frac{1}{2} \oint_S \text{Re}[\hat{\mathbf{E}} \times \hat{\mathbf{H}}^*] \cdot d\mathbf{S} + \frac{1}{2} \int_V \sigma |\hat{\mathbf{E}}|^2 dV$$

Valid for time-harmonic steady state



Plane Wave

Unitary vector representing the direction of propagation

Electric and magnetic fields are mutually orthogonal

Electric and magnetic fields are orthogonal to propagation direction

Wave-number

$$\hat{\mathbf{E}}(\mathbf{r}, \omega) = \mathbf{E}_0(\omega) e^{-j\mathbf{k}\mathbf{n}\cdot\mathbf{r}}$$
$$\hat{\mathbf{H}}(\mathbf{r}, \omega) = \frac{k}{\omega\mu} [\mathbf{n} \times \mathbf{E}_0(\omega)] e^{-j\mathbf{k}\mathbf{n}\cdot\mathbf{r}}$$
$$\mathbf{n} \cdot \mathbf{E}_0(\omega) = 0$$
$$\mathbf{n} \cdot \mathbf{H}_0(\omega) = 0$$
$$k^2 = -j\omega\mu(\sigma + j\omega\varepsilon)$$

The simplest wave solution of Maxwell('s) equations

Plane Wave Characteristics

$$k = \sqrt{-j\omega\mu(\sigma + j\omega\varepsilon)}$$

$$\operatorname{Re}[k] > 0; \operatorname{Im}[k] < 0$$

$$\lambda = \frac{2\pi}{\operatorname{Re}[k]}$$

$$v_f = \frac{\omega}{\operatorname{Re}[k]}$$

$$Z = \frac{\omega\mu}{k}$$

$$\delta = -\frac{1}{\operatorname{Im}[k]}$$

Vacuum



$$k = \frac{\omega}{c_0}$$

$$\operatorname{Re}[k] > 0; \operatorname{Im}[k] = 0$$

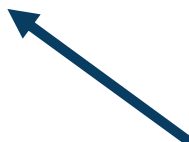
$$\lambda = \frac{c_0}{f}$$

$$v_f = c_0$$

$$Z = c_0\mu_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 377 \Omega$$

$$\delta \rightarrow \infty$$

General isotropic material



Cycle Mean Power Density of a Plane Wave

Power propagation coincides with phase propagation

$$\langle \mathbf{E}(\mathbf{r}, t) \times \mathbf{H}(\mathbf{r}, t) \rangle = \frac{1}{2} \frac{\operatorname{Re}[k]}{\omega \mu} |\mathbf{E}_0(\omega)|^2 e^{2\operatorname{Im}[k] \cdot \mathbf{n} \cdot \mathbf{r}} \mathbf{n}$$



Guided TEM Wave

Wave propagation identical to a planewave

$$k^2 = -j\omega\mu(\sigma + j\omega\varepsilon)$$

Geometry of a planewave

$$\hat{\mathbf{E}}(\mathbf{r}, \omega) = \mathbf{E}_\perp(x, y, \omega) e^{-jkz}$$

$$\hat{\mathbf{H}}(\mathbf{r}, \omega) = \mathbf{H}_\perp(x, y, \omega) e^{-jkz}$$

$$\hat{\mathbf{H}} = \frac{k}{\omega\mu} (\mathbf{z}_0 \times \hat{\mathbf{E}})$$

Transversal field pattern is static-like

$$\begin{aligned} \Delta_\perp \mathbf{E}_\perp &= 0 \\ \Delta_\perp \mathbf{H}_\perp &= 0 \end{aligned}$$

$$\mathbf{n} \times \mathbf{E}_\perp = 0$$

Boundary condition
on the conductor

Generalization of a planewave



Circuit Parameters of the TEM Wave

$$\hat{U}(z, \omega) = \hat{U}_0(\omega) e^{-jkz}$$

$$\hat{I}(z, \omega) = \hat{I}_0(\omega) e^{-jkz}$$

$$\hat{I}_0(\omega) = \oint_l \mathbf{H}_\perp \cdot d\mathbf{l} = \frac{k}{\omega\mu} \cdot \frac{Q_{\text{pul}}}{\varepsilon}$$

$$\hat{U}_0(\omega) = -\int_A^B \mathbf{E}_\perp \cdot d\mathbf{l} = \frac{\omega\mu}{k} \cdot \frac{\Phi_{\text{pul}}}{\mu}$$

Enclosing conductor

Between conductor

$$Z_{\text{TRL}} = \frac{\hat{U}_0(\omega)}{\hat{I}_0(\omega)} = \frac{\omega\mu}{k} \cdot \frac{\varepsilon}{C_{\text{pul}}} = \frac{\omega\mu}{k} \cdot \frac{L_{\text{pul}}}{\mu} = \sqrt{\frac{L_{\text{pul}}}{C_{\text{pul}}}}$$

$$v_{\text{phase}} = \frac{1}{\sqrt{C_{\text{pul}} L_{\text{pul}}}} = \frac{1}{\sqrt{\varepsilon\mu}}$$

Per unit length

Velocity of phase propagation



The Telegraph Equations

$$\frac{\partial U(z,t)}{\partial z} = -L_{\text{pul}} \frac{\partial I(z,t)}{\partial t}$$

$$\frac{\partial I(z,t)}{\partial z} = -C_{\text{pul}} \frac{\partial U(z,t)}{\partial t}$$

Circuit analog of Maxwell's equations





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