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TOPIC: **MAXWELL'S EQUATIONS**


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## MAXWELL'S EQUATIONS

Maxwell's equations are a set of four partial differential equations that relate the electric and magnetic fields to their sources, charge density and current density. These equations can be combined to show that light is an electromagnetic wave. Individually, the equations are known as Gauss's law, Gauss's law for magnetism, Faraday's law of induction, and Ampère's law with Maxwell's correction. The set of equations is named after James Clerk Maxwell.

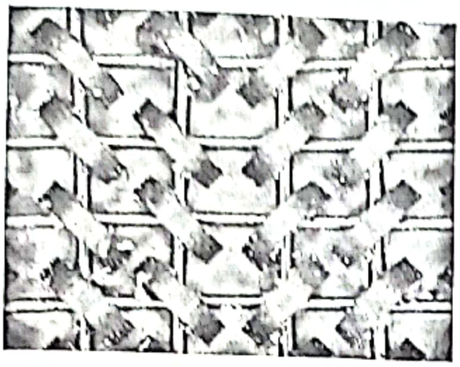
These four equations, together with the Lorentz force law are the complete set of laws of classical electromagnetism. The Lorentz force law itself was actually derived by Maxwell under the name of Equation for Electromotive Force and was one of an earlier set of eight equations by Maxwell.

### Conceptual description

This section will conceptually describe each of the four Maxwell's equations, and also how they link together to explain the origin of electromagnetic radiation such as light. The exact equations are set out in later sections of this article.

- Gauss' law describes how an electric field is generated by electric charges: The electric field tends to point away from positive charges and towards negative charges. More technically, it relates the electric flux through any hypothetical closed "Gaussian surface" to the electric charge within the surface.

- Gauss' law for magnetism states that there are no "magnetic charges" (also called magnetic monopoles), analogous to electric charges.[1] Instead the magnetic field is generated by a configuration called a dipole, which has no magnetic charge but resembles a positive and negative charge inseparably bound together. Equivalent technical statements are that the total magnetic flux through any Gaussian surface is zero, or that the magnetic field is a solenoidal vector field.



An Wang's magnetic core memory (1954) is an application of Ampere's law. Each core stores one bit of data.

- Faraday's law describes how a changing magnetic field can create ("induce") an electric field.[1] This aspect of electromagnetic induction is the operating principle behind many electric generators: A bar magnet is rotated to create a changing magnetic field, which in turn generates an electric field in a nearby wire. (Note: The "Faraday's law" that occurs in Maxwell's equations is a bit different than the version originally written by Michael Faraday. Both versions are equally true laws of physics, but they have different scope, for example whether "motional EMF" is included. See Faraday's law of induction for details.)

- Ampère's law with Maxwell's correction states that magnetic fields can be generated in two ways: by electrical current (this was the original "Ampère's law") and by changing electric fields (this was "Maxwell's correction").

Maxwell's correction to Ampère's law is particularly important: It means that a changing magnetic field creates an electric field, and a changing electric field creates a magnetic field.[1][2] Therefore, these equations allow self-sustaining "electromagnetic waves" to travel through empty space (see electromagnetic wave equation).

The speed calculated for electromagnetic waves, which could be predicted from experiments on charges and currents,[3] exactly matches the speed of light; indeed, light is one form of electromagnetic radiation (as are X-rays, radio waves, and others). Maxwell understood the connection between electromagnetic waves and light in 1864, thereby unifying the previously-separate fields of electromagnetism and optics.

## [edit] General formulation

The equations in this section are given in SI units. Unlike the equations of mechanics (for example), Maxwell's equations are not unchanged in other unit systems. Though the general form remains the same, various definitions get changed and different constants appear at different places. Other than SI (used in engineering), the units commonly used are Gaussian units (based on the cgs system and considered to have some theoretical advantages over SI[4]), Lorentz-Heaviside units (used mainly in particle physics) and Planck units (used in theoretical physics). See below for CGS-Gaussian units.

Two equivalent, general formulations of Maxwell's equations follow. The first separates bound charge and bound current (which arise in the context of dielectric and/or magnetized materials) from free charge and free current (the more conventional type of charge and current). This separation is useful for calculations involving dielectric or magnetized materials. The second formulation treats all charge equally, combining free and bound charge into total charge (and likewise with current). This is the more fundamental or microscopic point of view, and is particularly useful when no dielectric or magnetic material is present. More details, and a proof that these two formulations are mathematically equivalent, are given in section 4.

Symbols in bold represent vector quantities, and symbols in italics represent scalar quantities. The definitions of terms used in the two tables of equations are given in another table immediately following.

Formulation in terms of free charge and current

| Name | Differential form | Integral form |
|---|---|---|
| Gauss's law | $\nabla \cdot \mathbf{D} = \rho_f$ | $\oiint_{\partial V} \mathbf{D} \cdot d\mathbf{A} = Q_f(V)$ |
| Gauss's law for magnetism | $\nabla \cdot \mathbf{B} = 0$ | $\oiint_{\partial V} \mathbf{B} \cdot d\mathbf{A} = 0$ |

| | | |
|---|---|---|
| Maxwell–Faraday equation (Faraday's law of induction) | $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ | $\oint_{\partial S} \mathbf{E} \cdot \mathrm{d}\mathbf{l} = -\frac{\partial \Phi_{B,S}}{\partial t}$ |
| Ampère's circuital law (with Maxwell's correction) | $\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t}$ | $\oint_{\partial S} \mathbf{H} \cdot \mathrm{d}\mathbf{l} = I_{f,S} + \frac{\partial \Phi_{D,S}}{\partial t}$ |

*Formulation in terms of total charge and current*[note 1]

| Name | Differential form | Integral form |
|---|---|---|
| Gauss's law | $\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$ | $\oiint_{\partial V} \mathbf{E} \cdot \mathrm{d}\mathbf{A} = \frac{Q(V)}{\varepsilon_0}$ |
| Gauss's law for magnetism | $\nabla \cdot \mathbf{B} = 0$ | $\oiint_{\partial V} \mathbf{B} \cdot \mathrm{d}\mathbf{A} = 0$ |
| Maxwell–Faraday equation (Faraday's law of induction) | $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ | $\oint_{\partial S} \mathbf{E} \cdot \mathrm{d}\mathbf{l} = -\frac{\partial \Phi_{B,S}}{\partial t}$ |
| Ampère's circuital law (with Maxwell's correction) | $\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$ | $\oint_{\partial S} \mathbf{B} \cdot \mathrm{d}\mathbf{l} = \mu_0 I_S + \mu_0 \varepsilon_0 \frac{\partial \Phi_{E,S}}{\partial t}$ |

*The following table provides the meaning of each symbol and the SI unit of measure:*

*Definitions and units*

| Symbol | Meaning (first term is the most common) | SI Unit of Measure |
|---|---|---|
| **E** | electric field | volt per meter or, equivalently, newton per coulomb |
| **B** | magnetic field also called the magnetic induction also called the magnetic field density also called the magnetic flux density | tesla, or equivalently, weber per square meter, volt-second per square meter |
| **D** | electric displacement field also called the electric induction also called the electric flux density | coulombs per square meter or equivalently, newton per volt-meter |
| **H** | magnetizing field also called auxiliary magnetic field also called magnetic field intensity also called magnetic field | ampere per meter |
| $\nabla\cdot$ | the divergence operator | per meter (factor contributed by applying either operator) |
| $\nabla\times$ | the curl operator | |
| $\frac{\partial}{\partial t}$ | partial derivative with respect to time | per second (factor contributed by applying the operator) |
| $d\mathbf{A}$ | differential vector element of surface | square meters |

| | | |
|---|---|---|
| | *area A, with infinitesimally small magnitude and direction normal to surface S* | |
| **dl** | *differential vector element of path length tangential to the path/curve* | *meters* |
| $\varepsilon_0$ | *permittivity of free space, also called the electric constant, a universal constant* | *farads per meter* |
| $\mu_0$ | *permeability of free space, also called the magnetic constant, a universal constant* | *henries per meter, or newtons per ampere squared* |
| $\rho_f$ | *free charge density (not including bound charge)* | *coulombs per cubic meter* |
| $\rho$ | *total charge density (including both free and bound charge)* | *coulombs per cubic meter* |
| $\mathbf{J}_f$ | *free current density (not including bound current)* | *amperes per square meter* |
| **J** | *total current density (including both free and bound current)* | *amperes per square meter* |
| $Q_f(V)$ | *net free electric charge within the three-dimensional volume V (not including bound charge)* | *coulombs* |

| | | |
|---|---|---|
| $Q(V)$ | net electric charge within the three-dimensional volume V (including both free and bound charge) | coulombs |
| $\oint_{\partial S} \mathbf{E} \cdot d\mathbf{l}$ | line integral of the electric field along the boundary ∂S of a surface S (∂S is always a closed curve). | joules per coulomb |
| $\oint_{\partial S} \mathbf{B} \cdot d\mathbf{l}$ | line integral of the magnetic field over the closed boundary ∂S of the surface S | tesla-meters |
| $\oiint_{\partial V} \mathbf{E} \cdot d\mathbf{A}$ | the electric flux (surface integral of the electric field) through the (closed) surface $\partial V$ (the boundary of the volume V) | joule-meter per coulomb |
| $\oiint_{\partial V} \mathbf{B} \cdot d\mathbf{A}$ | the magnetic flux (surface integral of the magnetic B-field) through the (closed) surface $\partial V$ (the boundary of the volume V) | tesla meters-squared or webers |
| $\iint_S \mathbf{B} \cdot d\mathbf{A} = \Phi_{B,S}$ | magnetic flux through any surface S, not necessarily closed | webers or equivalently, volt-seconds |

| | | |
|---|---|---|
| $\iint_S \mathbf{E} \cdot \mathrm{d}\mathbf{A} = \Phi_{E,S}$ | *electric flux through any surface S, not necessarily closed* | *joule-meters per coulomb* |
| $\iint_S \mathbf{D} \cdot \mathrm{d}\mathbf{A} = \Phi_{D,S}$ | *flux of electric displacement field through any surface S, not necessarily closed* | *coulombs* |
| $\iint_S \mathbf{J}_f \cdot \mathrm{d}\mathbf{A} = I_{f,s}$ | *net free electrical current passing through the surface S (not including bound current)* | *amperes* |
| $\iint_S \mathbf{J} \cdot \mathrm{d}\mathbf{A} = I_S$ | *net electrical current passing through the surface S (including both free and bound current)* | *amperes* |