Quantum Mechanics_electromagnetic field

An **electromagnetic field** (also **EMF** or **EM field**) is a physical field produced by electrically charged objects. It affects the behavior of charged objects in the vicinity of the field. The electromagnetic field extends indefinitely throughout space and describes the electromagnetic interaction. It is one of the fourfundamental forces of nature (the others aregravitation, weak interaction and strong interaction).

The field can be viewed as the combination of anElectric field and a Magnetic field. The electric field is produced by stationary charges, and the magnetic field by moving charges (currents); these two are often described as the sources of the field. The way in which charges and currents interact with the electromagnetic field is described by Maxwell's equations and the Lorentz force law.

From a classical perspective in the history of electromagnetism, the electromagnetic field can be regarded as a smooth, continuous field, propagated in a wavelike manner; whereas from the perspective of quantum field theory, the field is seen as quantized, being composed of individualparticles.[*citation needed*]

Structure of the electromagnetic field

The electromagnetic field may be viewed in two distinct ways: a continuous structure or a discrete structure.

Continuous structure

Classically, electric and magnetic fields are thought of as being produced by smooth motions of charged objects. For example, oscillating charges produce electric and magnetic fields that may be viewed in a 'smooth', continuous, wavelike fashion. In this case, energy is viewed as being transferred continuously through the electromagnetic field between any two locations. For instance, the metal atoms in a radio transmitter appear to transfer energy continuously. This view is useful to a certain extent (radiation of low frequency), but problems are found at high frequencies (see ultraviolet catastrophe).

Discrete structure

The electromagnetic field may be thought of in a more 'coarse' way. Experiments reveal that in some circumstances electromagnetic energy transfer is better described as being carried in the form of packets called quanta (in this case,photons) with a fixed frequency. Planck's relation links the energy *E* of a photon to its frequency ν through the equation:[1]

$$E = h\nu$$

where *h* is Planck's constant, named in honor of Max Planck, and ν is the frequency of the photon . Although modern quantum optics tells us that there also is a semi-classical explanation of the photoelectric effect—the emission of electrons from metallic surfaces subjected to Electromagnetic radiation—the photon was historically (although not strictly necessarily) used to explain certain observations. It is found that increasing the intensity of the incident radiation (so long as one remains in the linear regime) increases only the number of electrons ejected, and has almost no effect on the energy distribution of their ejection. Only the frequency of the radiation is relevant to the energy of the ejected electrons.

This quantum picture of the electromagnetic field (which treats it as analogous toharmonic oscillators) has proved very successful, giving rise to quantum electrodynamics, a quantum field theory describing the interaction of electromagnetic radiation with charged matter. It also gives rise to quantum optics, which is different from quantum electrodynamics in that the matter itself is modelled using quantum mechanics rather than quantum field theory.

Dynamics of the electromagnetic field

In the past, electrically charged objects were thought to produce two different, unrelated types of field associated with their charge property. An **electric field**is produced when the charge is stationary with respect to an observer measuring the properties of the charge, and a **magnetic field** (as well as an electric field) is produced when the charge moves (creating an electric current) with respect to this observer. Over time, it was realized that the electric and magnetic fields are better thought of as two parts of a greater whole — the electromagnetic field. Recall that "until 1831 electricity and magnetism had been viewed as unrelated phenomena. In 1831, Michael Faraday, one of the great thinkers of his time, made the seminal observation that time-varying magnetic fields could induce electric currents and then, in 1864, James Clerk Maxwell published his famous paper on a dynamical theory of the electromagnetic field. See Maxwell 1864 5, page 499; also David J. Griffiths (1999), Introduction to electrodynamics, third Edition, ed. Prentice Hall, pp. 559-562"(as quoted in Gabriela, 2009).

Once this electromagnetic field has been produced from a given charge distribution, other charged objects in this field will experience a force (in a similar way that planets experience a force in the gravitational field of the Sun). If these other charges and currents are comparable in size to the sources producing the above electromagnetic field, then a new net electromagnetic field will be produced. Thus, the electromagnetic field may be viewed as a dynamic entity that causes other charges and currents to move, and which is also affected by them. These interactions are described by Maxwell's equations and the Lorentz force law. (This discussion ignores the radiation reaction force.)

Electromagnetic field as a feedback loop

The behavior of the electromagnetic field can be resolved into four different parts of a loop:

- the electric and magnetic fields are generated by electric charges,
- the electric and magnetic fields interact with each other,
- the electric and magnetic fields produce forces on electric charges,
- the electric charges move in space.

A common misunderstanding is that (a) the quanta of the fields act in the same manner as (b) the charged particles that generate the fields. In our everyday world, charged **particles**, such as electrons, move slowly through matter, typically on the order of a few inches (or centimeters) per second[*citation needed*], but **fields** propagate at the speed of light - approximately 300 thousand kilometers (or 186 thousand miles) a second. The mundane speed difference between charged particles and field quanta is on the order of one to a million, more or less. Maxwell's equations relate (a) the presence and movement of charged particles with (b) the generation of fields. Those fields can then affect the force on, and can then move other slowly moving charged particles. Charged particles can move at relativistic speeds nearing field propagation speeds, but, as Einsteinshowed[*citation needed*], this requires enormous field energies, which are not present in our everyday experiences with electricity, magnetism, matter, and time and space.

The feedback loop can be summarized in a list, including phenomena belonging to each part of the loop:

- charged particles generate electric and magnetic fields

- the fields interact with each other
    - changing electric field acts like a current, generating 'vortex' of magnetic field
    - Faraday induction: changing magnetic field induces (negative) vortex of electric field
    - Lenz's law: negative feedback loop between electric and magnetic fields
- fields act upon particles
    - Lorentz force: force due to electromagnetic field
        - electric force: same direction as electric field
        - magnetic force: perpendicular both to magnetic field and to velocity of charge
- particles move
    - current is movement of particles
- particles generate more electric and magnetic fields; cycle repeats

Mathematical description

Main article: Mathematical descriptions of the electromagnetic field

There are different mathematical ways of representing the electromagnetic field. The first one views the electric and magnetic fields as three-dimensional vector fields. These vector fields each have a value defined at every point of space and time and are thus often regarded as functions of the space and time coordinates. As such, they are often written as **E**(x, y, z, t) (Electric field) and **B**(x, y, z, t) (Magnetic field).

If only the Electric field (**E**) is non-zero, and is constant in time, the field is said to be an electrostatic field. Similarly, if only the Magnetic field (**B**) is non-zero and is constant in time, the field is said to be a magnetostatic field. However, if either the electric or magnetic field has a time-dependence, then both fields must be considered together as a coupled electromagnetic field using Maxwell's equations.[2]

With the advent of special relativity, physical laws became susceptible to the formalism of tensors. Maxwell's equations can be written in tensor form, generally viewed by physicists as a more elegant means of expressing physical laws.

The behaviour of electric and magnetic fields, whether in cases of electrostatics, magnetostatics, or electrodynamics (electromagnetic fields), is governed in a vacuum by Maxwell's equations. In the vector field formalism, these are:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$ (Gauss's law)

$$\nabla \cdot \mathbf{B} = 0$$ (Gauss's law for magnetism)

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$ (Faraday's law)

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$ (Ampère-Maxwell law)

where ρ is the charge density, which can (and often does) depend on time and position, ϵ_0 is the permittivity of free space, μ_0 is the permeability of free space, and J is the current density vector, also a function of time and position. The units used above are the standard SI units. Inside a linear material, Maxwell's equations change by switching the permeability and permittivity of free space with the permeability and permittivity of the linear material in question. Inside other materials which possess more complex responses to electromagnetic fields, these terms are often represented by complex numbers, or tensors.

The Lorentz force law governs the interaction of the electromagnetic field with charged matter.

When a field travels across to different media, the properties of the field change according to the various boundary conditions. These equations are derived from Maxwell's equations. The tangential components of the electric and magnetic fields as they relate on the boundary of two media are as follows:[3]

$$\mathbf{E_1} = \mathbf{E_2}$$

$$\mathbf{H_1} = \mathbf{H_2}$$ (current-free)

$$\mathbf{D_1} = \mathbf{D_2}$$ (charge-free)

$$\mathbf{B_1} = \mathbf{B_2}$$

The angle of refraction of an electric field between media is related to the permittivity (ε) of each medium:

$$\frac{\tan\theta_1}{\tan\theta_2} = \frac{\varepsilon_{r2}}{\varepsilon_{r1}}$$

The angle of refraction of a magnetic field between media is related to the permeability (μ) of each medium:

$$\frac{\tan\theta_1}{\tan\theta_2} = \frac{\mu_{r2}}{\mu_{r1}}$$

Properties of the field

Reciprocal behavior of electric and magnetic fields

The two Maxwell equations, Faraday's Law and the Ampère-Maxwell Law, illustrate a very practical feature of the electromagnetic field. Faraday's Law may be stated roughly as 'a changing magnetic field creates an electric field'. This is the principle behind the electric generator.

Ampere's Law roughly states that 'a changing electric field creates a magnetic field'. Thus, this law can be applied to generate a magnetic field and run anelectric motor.

Light as an electromagnetic disturbance

Maxwell's equations take the form of an electromagnetic wave in an area that is very far away from any charges or currents (free space) – that is, where ρ and Jare zero. It can be shown, that, under these conditions, the electric and magnetic fields satisfy the electromagnetic wave equation:[4]

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{E} = 0$$
$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{B} = 0$$

James Clerk Maxwell was the first to obtain this relationship by his completion ofMaxwell's equations with the addition of a Displacement current term toAmpere's Circuital law.

Relation to and comparison with other physical fields

Main article: Fundamental forces

This section requires expansion. *(June 2008)*

Being one of the four fundamental forces of nature, it is useful to compare the electromagnetic field with the gravitational, strong and weak fields. The word 'force' is sometimes replaced by 'interaction' because modern particle physicsmodels electromagnetism as an exchange of particles known as gauge bosons.

Electromagnetic and gravitational fields

Sources of electromagnetic fields consist of two types of charge – positive and negative. This contrasts with the sources of the gravitational field, which are masses. Masses are sometimes described as *gravitational charges*, the important feature of them being that there are only positive masses and no negative masses. Further, gravity differs from electromagnetism in that positive masses attract other positive masses whereas same charges in electromagnetism repel each other.

The relative strengths and ranges of the four interactions and other information are tabulated below:

Theory	Interaction	mediator	Relative Magnitude	Behavior	Range
Chromodynamics	strong interaction	gluon	10^{38}	1	10^{-15}m
electrodynamics	Electromagnetic interaction	photon	10^{36}	$1/r^2$	infinite
Flavordynamics	weak interaction	W and Z bosons	10^{25}	$1/r^5$ to $1/r^7$	10^{-16}m
Geometrodynamics	gravitation	graviton	10^0	$1/r^2$	infinite

Applications

This section requires expansion. *(February 2012)*

Static E and M fields and static EM fields

Main articles: Electrostatics, Magnetostatics and Magnetism

When an EM field (see Electromagnetic tensor) is not varying in time, it may be seen as a purely electrical field or a purely magnetic field, or a mixture of both. However the general case of a static EM field with both electric and magnetic components present, is the case that appears to most observers. Observers who see only an electric or magnetic field component of a static EM field, have the other (electric or magnetic) component suppressed, due to the special case of the immobile state of the charges that produce the EM field in that case. In such cases the other component becomes manifest in other observer frames.

A consequence of this, is that any case that seems to consist of a "pure" static electric or magnetic field, can be converted to an EM field, with both E and M components present, by simply moving the observer into a frame of referencewhich is moving with regard to the frame in which only the “pure” electric or magnetic field appears. That is, a pure static electric field will show the familiar magnetic field associated with a current, in any frame of reference where the charge moves. Likewise, any new motion of a charge in a region that seemed previously to contain only a magnetic field, will show that that the space now contains an electric field as well, which will be found to produces an additional Lorentz force upon the moving charge.

Thus, Electrostatics, as well as Magnetism and Magnetostatics, are now seen as studies of the static EM field when a particular frame has been selected to suppress the other type of field, and since an EM field with both electric and magnetic will appear in any other frame, these "simpler" effects are merely the observer's. The "applications" of all such non-time varying (static) fields are discussed in the main articles linked in this section.

Time-varying EM fields in Maxwell's equations

Main articles: near and far field, near field optics, virtual particle, dielectric heating and magnetic induction

An EM field that varies in time has two "causes" in Maxwell's equations. One is charges and currents (so-called "sources"), and the other cause for an E or M field is a change in the other type of field (this last cause also appears in "free space" very far from currents and charges).

An electromagnetic field very far from currents and charges (sources) is calledElectromagnetic radiation (EMR) since it radiates from the charges and currents in the source, and has no "feedback" effect on them, and is also not affected directly by them in the present time (rather, it is indirectly produced by a sequences of changes in fields radiating out from them in the past). EMR consists of the radiations in the electromagnetic spectrum, including radio waves, microwave,infrared, visible light, ultraviolet light, X-rays, and gamma rays. The many commercial applications of these radiations are discussed in the named and linked articles.

A notable application of visible light is that this type of energy from the Sun powers all life on Earth that either makes or uses oxygen.

A changing electromagnetic field which is physically close to currents and charges (see near and far field for a definition of "close") will have a dipolecharacteristic that is dominated by either a changing electric dipole, or a changingmagnetic dipole. This type of dipole field near sources is called an electromagnetic *near-field*.

Changing *electric* dipole fields, as such, are used commercially as near-fields mainly as a source of dielectric heating. Otherwise, they appear parasitically around conductors which absorb EMR, and around antennas which have the purpose of generating EMR at greater distances.

Changing *magnetic* dipole fields (i.e., magnetic near-fields) are used commercially for many types of magnetic induction devices. These include motors and electrical transformers at low frequencies, and devices such as metal detectorsand MRI scanner coils at higher frequencies. Sometimes these high-frequency magnetic fields change at radio frequencies without being far-field waves and thus radio waves; see RFID tags. See also near-field communication. Further uses of near-field EM effects commercially, may be found in the article on virtual photons, since at the quantum level, these fields are represented by these particles. Far-field effects (EMR) in the quantum picture of radiation, are represented by ordinary photons.

Health and safety

The potential health effects of the very low frequency EMFs surrounding power lines and electrical devices are the subject of on-going research and a significant amount of public debate. The US National Institute for Occupational Safety and Health (NIOSH) has issued some cautionary advisories but stresses that the data is currently too limited to draw good conclusions.[5]

The potential effects of electromagnetic fields on human health vary widely depending on the frequency and intensity of the fields. For more information on the health effects due to specific parts of the electromagnetic spectrum, see the following articles:

- Static electric fields: see Electric shock
- Static magnetic fields: see MRI#Safety
- Extremely low frequency (ELF): see Power lines#Health concerns
- Radio frequency (RF): see Electromagnetic radiation and health
- Light: see Laser safety
- Ultraviolet (UV): see Sunburn
- Gamma rays: see Gamma ray
- Mobile telephony: see Mobile phone radiation and health

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