Faraday's law of induction

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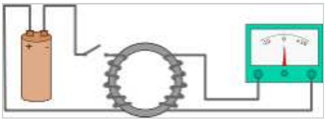
Faraday's law of induction is a basic law of electromagnetism predicting how a magnetic field will interact with an electric circuit to produce an electromotive force (EMF)—a phenomenon called electromagnetic induction. It is the fundamental operating principle of transformers, inductors, and many types of electrical motors, generators and solenoids.[1][2]

The **Maxwell–Faraday equation** is a generalization of Faraday's law, and forms one of Maxwell's equations.

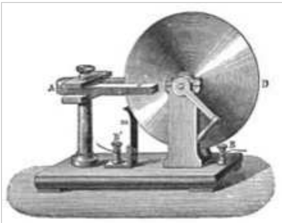
Contents

History



A diagram of Faraday's iron ring apparatus. Change in the magnetic flux of the left coil induces a current in the right coil.[3]

Electromagnetic induction was discovered independently by Michael Faraday in 1831 and Joseph Henry in 1832.[4] Also, Faraday was the first to publish the results of his experiments.[5][6] In Faraday's first experimental demonstration of electromagnetic induction (August 29, 1831[7]), he wrapped two wires around opposite sides of an iron ring or "torus" (an arrangement similar to a modern toroidal transformer). Based on his assessment of recently discovered properties of electromagnets, he expected that when current started to flow in one wire, a sort of wave would travel through the ring and cause some electrical effect on the opposite side. He plugged one wire into a galvanometer, and watched it as he connected the other wire to a battery. Indeed, he saw a transient current (which he called a "wave of electricity") when he connected the wire to the battery, and another when he disconnected it.[8] This induction was due to the change in magnetic flux that occurred when the battery was connected and disconnected.[3] Within two months, Faraday had found several other manifestations of electromagnetic induction. For example, he saw transient currents when he quickly slid a bar magnet in and out of a coil of wires, and he generated a steady (DC) current by rotating a copper disk near the bar magnet with a sliding electrical lead ("Faraday's disk").[9]



Faraday's disk (see homopolar generator)

Michael Faraday explained electromagnetic induction using a concept he called lines of force. However, scientists at the time widely rejected his theoretical ideas, mainly because they were not formulated mathematically.[10] An exception was James Clerk Maxwell, who used Faraday's ideas as the basis of his quantitative electromagnetic theory.[10][11][12] In Maxwell's papers, the time-varying aspect of electromagnetic induction is expressed as a differential equation which Oliver Heaviside referred to as Faraday's law even though it is different from the original version of Faraday's law, and does not describe motional EMF. Heaviside's version (see Maxwell–Faraday equation below) is the form recognized today in the group of equations known as Maxwell's equations.

Lenz's law, formulated by Heinrich Lenz in 1834, describes "flux through the circuit", and gives the direction of the induced EMF and current resulting from electromagnetic induction (elaborated upon in the examples below).

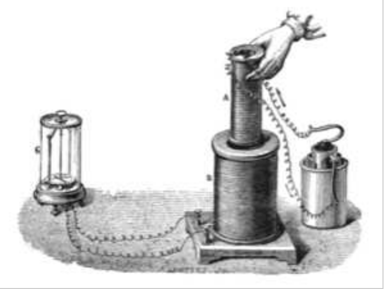
Faraday's law

Qualitative statement

The most widespread version of Faraday's law states:

> The induced electromotive force in any closed circuit is equal to the negative of the time rate of change of the magnetic flux enclosed by the circuit.[14][15]

This version of Faraday's law strictly holds only when the closed circuit is a loop of infinitely thin wire,[16] and is invalid in other circumstances as discussed below. A different version, the Maxwell–Faraday equation (discussed below), is valid in all circumstances.

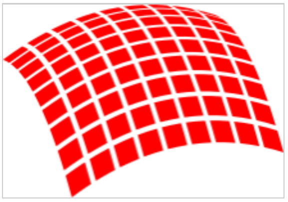


Faraday's experiment showing induction between coils of wire: The liquid battery *(right)* provides a current which flows through the small coil *(A)*, creating a magnetic field. When the coils are stationary, no current is induced. But when the small coil is moved in or out of the large coil *(B)*, the magnetic flux through the large coil changes, inducing a current which is detected by the galvanometer *(G)*.[13]

Quantitative

Faraday's law of induction makes use of the magnetic flux Φ_B through a hypothetical surface Σ whose boundary is a wire loop. Since the wire loop may be moving, we write Σ(t) for the surface. The magnetic flux is defined by a surface integral:

$$\Phi_B = \iint\limits_{\Sigma(t)} \mathbf{B}(\mathbf{r}, t) \cdot d\mathbf{A} \ ,$$



The definition of surface integral relies on splitting the surface Σ into small surface elements. Each element is associated with a vector $d\mathbf{A}$ of magnitude equal to the area of the element and with direction normal to the element and pointing “outward” (with respect to the orientation of the surface).

where $d\mathbf{A}$ is an element of surface area of the moving surface Σ(t), **B** is the magnetic field (also called "magnetic flux density"), and $\mathbf{B}\cdot d\mathbf{A}$ is a vector dot product (the infinitesimal amount of magnetic flux). In more visual terms, the magnetic flux through the wire loop is proportional to the number of magnetic flux lines that pass through the loop.

When the flux changes—because **B** changes, or because the wire loop is moved or deformed, or both—Faraday's law of induction says that the wire loop acquires an EMF, $\mathcal{E}$, defined as the energy available from a unit charge that has travelled once around the wire loop.[16][17][18][19] Equivalently, it is the voltage that would be measured by cutting the wire to create an open circuit, and attaching a voltmeter to the leads.

Faraday's law states that the EMF is also given by the rate of change of the magnetic flux:

$$\mathcal{E} = -\frac{d\Phi_B}{dt},$$

where $\mathcal{E}$ is the electromotive force (EMF) and Φ_B is the magnetic flux. The direction of the electromotive force is given by Lenz's law.

For a tightly wound coil of wire, composed of N identical turns, each with the same Φ_B, Faraday's law of induction states that[20][21]

$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

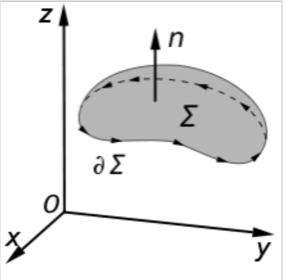
where N is the number of turns of wire and Φ_B is the magnetic flux through a *single* loop.

Maxwell–Faraday equation

The Maxwell–Faraday equation is a generalisation of Faraday's law that states that a time-varying magnetic field is always accompanied by a spatially-varying, non-conservative electric field, and vice-versa. The Maxwell–Faraday equation is

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

(in SI units) where $\nabla\times$ is the curl operator and again $\mathbf{E}(\mathbf{r}, t)$ is the electric field and $\mathbf{B}(\mathbf{r}, t)$ is the magnetic field. These fields can generally be functions of position **r** and time t.



An illustration of Kelvin-Stokes theorem with surface **Σ** its boundary **∂Σ** and orientation ***n*** set by the right-hand rule.

The Maxwell–Faraday equation is one of the four Maxwell's equations, and therefore plays a fundamental role in the theory of classical electromagnetism. It can also be written in an **integral form** by the Kelvin-Stokes theorem:[22]

$$\boxed{\oint_{\partial \Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\int_{\Sigma} \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{A}}$$

where, as indicated in the figure:

$\mathbf{\Sigma}$ is a surface bounded by the closed contour $\partial\mathbf{\Sigma}$,

$\mathbf{E}$ is the electric field, $\mathbf{B}$ is the magnetic field.

$d\boldsymbol{\ell}$ is an infinitesimal vector element of the contour $\partial\mathbf{\Sigma}$,

$d\mathbf{A}$ is an infinitesimal vector element of surface $\mathbf{\Sigma}$. If its direction is orthogonal to that surface patch, the magnitude is the area of an infinitesimal patch of surface.

Both $d\boldsymbol{\ell}$ and $d\mathbf{A}$ have a sign ambiguity; to get the correct sign, the right-hand rule is used, as explained in the article Kelvin-Stokes theorem. For a planar surface Σ, a positive path element $d\boldsymbol{\ell}$ of curve $\partial\Sigma$ is defined by the right-hand rule as one that points with the fingers of the right hand when the thumb points in the direction of the normal $\mathbf{n}$ to the surface Σ.

The integral around $\partial\mathbf{\Sigma}$ is called a *path integral* or *line integral.*

Notice that a nonzero path integral for **E** is different from the behavior of the electric field generated by charges. A charge-generated **E**-field can be expressed as the gradient of a scalar field that is a solution to Poisson's equation, and has a zero path integral. See gradient theorem.

The integral equation is true for *any* path $\partial\mathbf{\Sigma}$ through space, and any surface $\mathbf{\Sigma}$ for which that path is a boundary.

If the path $\mathbf{\Sigma}$ is not changing in time, the equation can be rewritten:

$$\oint_{\partial \Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \int_{\Sigma} \mathbf{B} \cdot d\mathbf{A}.$$

The surface integral at the right-hand side is the explicit expression for the magnetic flux Φ_B through $\mathbf{\Sigma}$.

Proof of Faraday's law

The four Maxwell's equations (including the Maxwell–Faraday equation), along with the Lorentz force law, are a sufficient foundation to derive *everything* in classical electromagnetism.[16][17] Therefore it is possible to "prove" Faraday's law starting with these equations.[23][24] Click "show" in the box below for an outline of this proof. (In an alternative approach, not shown here but equally valid, Faraday's law could be taken as the starting point and used to "prove" the Maxwell–Faraday equation and/or other laws.)

Outline of proof of Faraday's law from Maxwell's equations and the Lorentz force law.

Consider the time-derivative of flux through a possibly moving loop, with area $\Sigma(t)$:

$$\frac{d\Phi_B}{dt} = \frac{d}{dt} \int_{\Sigma(t)} \mathbf{B}(t) \cdot d\mathbf{A}$$

The integral can change over time for two reasons: The integrand can change, or the integration region can change. These add linearly, therefore:

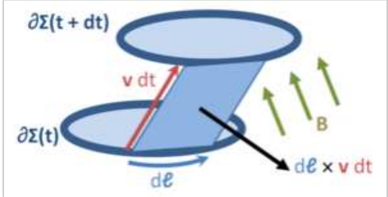
$$\left.\frac{d\Phi_B}{dt}\right|_{t=t_0} = \left(\int_{\Sigma(t_0)} \left.\frac{\partial \mathbf{B}}{\partial t}\right|_{t=t_0} \cdot d\mathbf{A} \right) + \left(\frac{d}{dt} \int_{\Sigma(t)} \mathbf{B}(t_0) \cdot d\mathbf{A} \right)$$

where t_0 is any given fixed time. We will show that the first term on the right-hand side corresponds to transformer EMF, the second to motional EMF (see above). The first term on the right-hand side can be rewritten using the integral form of the Maxwell–Faraday equation:

$$\int_{\Sigma(t_0)} \left.\frac{\partial \mathbf{B}}{\partial t}\right|_{t=t_0} \cdot d\mathbf{A} = -\oint_{\partial\Sigma(t_0)} \mathbf{E}(t_0) \cdot d\boldsymbol{\ell}$$

Next, we analyze the second term on the right-hand side:

$$\frac{d}{dt}\int_{\Sigma(t)} \mathbf{B}(t_0)\cdot d\mathbf{A}$$



Area swept out by vector element $d\boldsymbol{\ell}$ of curve $\partial\Sigma$ in time dt when moving with velocity $\mathbf{v}$.

This is the most difficult part of the proof; more details and alternate approaches can be found in references.[23][24][25] As the loop moves and/or deforms, it sweeps out a surface (see figure on right). The magnetic flux through this swept-out surface corresponds to the magnetic flux that is either entering or exiting the loop, and therefore this is the magnetic flux that contributes to the time-derivative. (This step implicitly uses Gauss's law for magnetism: Since the flux lines have no beginning or end, they can only get into the loop by getting cut through by the wire.) As a small part of the loop $d\boldsymbol{\ell}$ moves with velocity **v** for a short time dt, it sweeps out a vector area vector $d\mathbf{A} = \mathbf{v}\,dt \times d\boldsymbol{\ell}$. Therefore, the change in magnetic flux through the loop here is

$$\mathbf{B}\cdot(\mathbf{v}\,dt \times d\boldsymbol{\ell}) = -dt\,d\boldsymbol{\ell}\cdot(\mathbf{v}\times\mathbf{B})$$

Therefore:

$$\frac{d}{dt}\int_{\Sigma(t)} \mathbf{B}(t_0)\cdot d\mathbf{A} = -\oint_{\partial\Sigma(t_0)} (\mathbf{v}(t_0)\times\mathbf{B}(t_0))\cdot d\boldsymbol{\ell}$$

where **v** is the velocity of a point on the loop $\partial\Sigma$.

Putting these together,

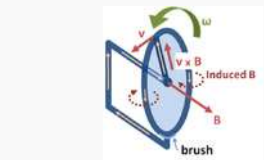
$$\left.\frac{d\Phi_B}{dt}\right|_{t=t_0} = \left(-\oint_{\partial\Sigma(t_0)} \mathbf{E}(t_0)\cdot d\boldsymbol{\ell}\right) + \left(-\oint_{\partial\Sigma(t_0)} (\mathbf{v}(t_0)\times\mathbf{B}(t_0))\cdot d\boldsymbol{\ell}\right)$$

Meanwhile, EMF is defined as the energy available per unit charge that travels once around the wire loop. Therefore, by the Lorentz force law,

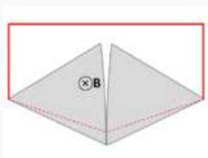
$$EMF = \oint (\mathbf{E} + \mathbf{v}\times\mathbf{B})\cdot \mathrm{d}\boldsymbol{\ell}$$

Combining these, $\frac{d\Phi_B}{dt} = -EMF$

"Counterexamples" to Faraday's law



Faraday's disc electric generator. The disc rotates with angular rate ω, sweeping the conducting radius circularly in the static magnetic field **B**. The magnetic Lorentz force **v × B** drives the current along the conducting radius to the conducting rim, and from there the circuit completes through the lower brush and the axle supporting the disc. This device generates an EMF and a current, although the shape of the "circuit" is constant and thus the flux through the circuit does not change with time.



A counterexample to Faraday's law when over-broadly interpreted. A wire (solid red lines) connects to two touching metal plates (silver) to form a circuit. The whole system sits in a uniform magnetic field, normal to the page. If the word "circuit" is interpreted as "primary path of current flow" (marked in red), then the magnetic flux through the "circuit" changes dramatically as the plates are rotated, yet the EMF is almost zero, which contradicts Faraday's law. After *Feynman Lectures on Physics* Vol. II page 17-3.

Although Faraday's law is always true for loops of thin wire, it can give the wrong result if naively extrapolated to other contexts.[16] One example is the homopolar generator (above left): A spinning circular metal disc in a homogeneous magnetic field generates a DC (constant in time) EMF. In Faraday's law, EMF is the time-derivative of flux, so a DC EMF is only possible if the magnetic flux is getting uniformly larger and larger perpetually. But in the generator, the magnetic field is constant and the disc stays in the same position, so no magnetic fluxes are growing larger and larger. So this example cannot be analyzed directly with Faraday's law.

Another example, due to Feynman,[16] has a dramatic change in flux through a circuit, even though the EMF is arbitrarily small. See figure and caption above right.

In both these examples, the changes in the current path are different from the motion of the material making up the circuit. The electrons in a material tend to follow the motion of the atoms that make up the material, due to scattering in the bulk and work function confinement at the edges. Therefore, motional EMF is generated when a material's atoms are moving through a magnetic field, dragging the electrons with them, thus subjecting the electrons to the Lorentz force. In the homopolar generator, the material's atoms are moving, even though the overall geometry of the circuit is staying the same. In the second example, the material's atoms are almost stationary, even though the overall geometry of the circuit is changing dramatically. On the other hand, Faraday's law always holds for thin wires, because there the geometry of the circuit always changes in a direct relationship to the motion of the material's atoms.

Although Faraday's law does not apply to all situations, the Maxwell–Faraday equation and Lorentz force law are always correct and can always be used directly.[16]

Both of the above examples can be correctly worked by choosing the appropriate path of integration for Faraday's law. Outside of context of thin wires, the path must never be chosen to go through the conductor in the shortest direct path. This is explained in detail in "The Electromagnetodynamics of Fluid" by W. F. Hughes and F. J. Young, John Wiley Inc. (1965).

Faraday's law and relativity

Two phenomena

Some physicists have remarked that Faraday's law is a single equation describing two different phenomena: the *motional EMF* generated by a magnetic force on a moving wire (see Lorentz force), and the *transformer EMF* generated by an electric force due to a changing magnetic field (due to the Maxwell–Faraday equation).

James Clerk Maxwell drew attention to this fact in his 1861 paper *On Physical Lines of Force*. In the latter half of Part II of that paper, Maxwell gives a separate physical explanation for each of the two phenomena.

A reference to these two aspects of electromagnetic induction is made in some modern textbooks.[26] As Richard Feynman states:[16]

> So the "flux rule" that the emf in a circuit is equal to the rate of change of the magnetic flux through the circuit applies whether the flux changes because the field changes or because the circuit moves (or both) ...
>
> Yet in our explanation of the rule we have used two completely distinct laws for the two cases – $\mathbf{v}\times\mathbf{B}$ for "circuit moves" and $\nabla\times\mathbf{E}=-\partial_t\mathbf{B}$ for "field changes".
>
> We know of no other place in physics where such a simple and accurate general principle requires for its real understanding an analysis in terms of *two different phenomena*.
>
> — Richard P. Feynman, *The Feynman Lectures on Physics*

Einstein's view

Reflection on this apparent dichotomy was one of the principal paths that led Einstein to develop special relativity:

> It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor.
>
> The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated.
>
> But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise—assuming equality of relative motion in the two cases discussed—to electric currents of the same path and intensity as those produced by the electric forces in the former case.

Examples of this sort, together with unsuccessful attempts to discover any motion of the earth relative to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest.

— *Albert Einstein, On the Electrodynamics of Moving Bodies*[27]

See also

- Eddy current
- Inductance
- Maxwell's equations
- Moving magnet and conductor problem
- Alternator
- Crosstalk
- Faraday paradox
- Vector calculus

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8. ^ *Michael Faraday*, by L. Pearce Williams, p. 182-3
9. ^ *Michael Faraday*, by L. Pearce Williams, p. 191–5
10. ^ *a b* *Michael Faraday*, by L. Pearce Williams, p. 510
11. ^ Maxwell, James Clerk (1904), *A Treatise on Electricity and Magnetism*, Vol. II, Third Edition. Oxford University Press, pp. 178–9 and 189.
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14. ^ "Faraday's Law, which states that the electromotive force around a closed path is equal to the negative of the time rate of change of magnetic flux enclosed by the path"Jordan, Edward; Balmain, Keith G. (1968). *Electromagnetic Waves and Radiating Systems* (2nd ed.). Prentice-Hall. p. 100.
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16. ^ *a b c d e f g* "The flux rule" is the terminology that Feynman uses to refer to the law relating magnetic flux to EMF.Richard Phillips Feynman, Leighton R B & Sands M L (2006). *The Feynman Lectures on Physics* (http://books.google.com/?id=zUt7AAAACAAJ&dq=intitle:Feynman+intitle:Lectures+intitle:on+intitle:Physics). San Francisco: Pearson/Addison-Wesley. Vol. II, pp. 17-2. ISBN 0-8053-9049-9.
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18. ^ Tipler and Mosca, *Physics for Scientists and Engineers*, p795, google books link (http://books.google.com/books?id=R2Nuh3Ux1AwC&pg=PA795)
19. ^ Note that different textbooks may give different definitions. The set of equations used throughout the text was chosen to be compatible with the special relativity theory.
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24. ^ *a b* Basic Theoretical Physics: A Concise Overview by Krey and Owen, p155, google books link (http://books.google.com/books?id=xZ_QelBmkxYC&pg=PA155)

25. ^ K. Simonyi, Theoretische Elektrotechnik, 5th edition, VEB Deutscher Verlag der Wissenschaften, Berlin 1973, equation 20, page 47
26. ^ Griffiths, David J. (1999). *Introduction to Electrodynamics* (http://www.amazon.com/gp/reader/013805326X/ref=sib_dp_pt/104-2951702-6987112#reader-link) (Third ed.). Upper Saddle River NJ: Prentice Hall. pp. 301–3. ISBN 0-13-805326-X. Note that the law relating flux to EMF, which this article calls "Faraday's law", is referred to in Griffiths' terminology as the "universal flux rule". Griffiths uses the term "Faraday's law" to refer to what article calls the "Maxwell–Faraday equation". So in fact, in the textbook, Griffiths' statement is about the "universal flux rule".
27. ^ A. Einstein, On the Electrodynamics of Moving Bodies (http://www.fourmilab.ch/etexts/einstein/specrel/specrel.pdf)

Further reading

- Maxwell, James Clerk (1881), *A treatise on electricity and magnetism, Vol. II*, Chapter III, §530, p. 178. (http://books.google.com/books?id=vAsJAAAAIAAJ&printsec=frontcover&dq=intitle:a+intitle:treatise+intitle:on+intitle:electricity+intitle:an+intitle:magnetism&cad=0_1#v=onepage&q&f=false) Oxford, UK: Clarendon Press. ISBN 0-486-60637-6.

External links

- A simple interactive Java tutorial on electromagnetic induction (http://www.magnet.fsu.edu/education/tutorials/java/electromagneticinduction/index.html) National High Magnetic Field Laboratory
- R. Vega *Induction: Faraday's law and Lenz's law* - Highly animated lecture (http://www.physics.smu.edu/~vega/em1304/lectures/lect13/lect13_f03.ppt)
- Notes from Physics and Astronomy HyperPhysics at Georgia State University (http://hyperphysics.phy-astr.gsu.edu/HBASE/hframe.html)
- Faraday's Law for EMC Engineers (http://www.learnemc.com/tutorials/Faraday/Faradays_Law.html)
- Tankersley and Mosca: *Introducing Faraday's law* (http://usna.edu/Users/physics/tank/Public/FaradaysLaw.pdf)
- A free java simulation on motional EMF (http://www.phy.hk/wiki/englishhtm/Induction.htm)