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wave equations describing the propagation of electromagnetic waves generated by nonzero source charges and currents Articles aboutElectromagnetism Electricity Magnetism History Textbooks Electrostatics Electric charge Coulomb's law Conductor Charge density Permittivity Electric dipole moment Electric field Electric potential Electric flux / potential energy Electrostatic discharge Gauss's law Induction Insulator Polarization density Static electricity Triboelectricity Magnetostatics Ampère's law Biot–Savart law Gauss's law for magnetism Magnetic field Magnetic flux Magnetic dipole moment Magnetic permeability Magnetic scalar potential Magnetization Magnetomotive force Magnetic vector potential Right-hand rule Electrodynamics Lorentz force law Electromagnetic induction Faraday's law Lenz's law Displacement current Maxwell's equations Electromagnetic field Electromagnetic pulse Electromagnetic radiation Maxwell tensor Poynting vector Liénard–Wiechert potential Jefimenko's equations Eddy current London equations Mathematical descriptions of the electromagnetic field Electrical network Alternating current Capacitance Direct current Electric current Electrolysis Current density Joule heating Electromotive force Impedance Inductance Ohm's law Parallel circuit Resistance Resonant cavities Series circuit Voltage Waveguides Covariant formulation Electromagnetic tensor(stress–energy tensor) Four-current Electromagnetic four-potential Scientists Ampère Biot Coulomb Davy Einstein Faraday Fizeau Gauss Heaviside Henry Hertz Joule Lenz Lorentz Maxwell Ørsted Ohm Ritchie Savart Singer Tesla Volta Weber Poisson vte In electromagnetism and applications, an inhomogeneous electromagnetic wave equation, or nonhomogeneous electromagnetic wave equation, is one of a set of wave equations describing the propagation of electromagnetic waves generated by nonzero source charges and currents. The source terms in the wave equations make the partial differential equations inhomogeneous, if the source terms are zero the equations reduce to the homogeneous electromagnetic wave equations. The equations follow from Maxwell's equations. Maxwell's equations For reference, Maxwell's equations are summarized below in SI units and Gaussian units. They govern the electric field E and magnetic field B due to a source charge density ρ and current density J: Name SI units Gaussian units Gauss's law ∇ ⋅ E = ρ ε 0 {\displaystyle abla \cdot \mathbf {E} ={\frac {\rho }{\varepsilon _{0}}}} ∇ ⋅ E = 4 π ρ {\displaystyle abla \cdot \mathbf {E} =4\pi \rho } Gauss's law for magnetism ∇ ⋅ B = 0 {\displaystyle abla \cdot \mathbf {B} =0} ∇ ⋅ B = 0 {\displaystyle abla \cdot \mathbf {B} =0} Maxwell–Faraday equation (Faraday's law of induction) ∇ × E = − ∂ B ∂ t {\displaystyle abla \times \mathbf {E} =-{\frac {\partial \mathbf {B} }{\partial t}}} ∇ × E = − 1 c ∂ B ∂ t {\displaystyle abla \times \mathbf {E} =-{\frac {1}{c}}{\frac {\partial \mathbf {B} }{\partial t}}} Ampère's circuital law (with Maxwell's addition) ∇ × B = μ 0 (J + ε 0 ∂ E ∂ t) {\displaystyle abla \times \mathbf {B} =\mu _{0}\left(\mathbf {J} +\varepsilon _{0}{\frac {\partial \mathbf {E} }{\partial t}}\right)} ∇ × B = 1 c (4 π J + ∂ E ∂ t) {\displaystyle abla \times \mathbf {B} ={\frac {1}{c}}\left(4\pi \mathbf {J} +{\frac {\partial \mathbf {E} }{\partial t}}\right)} where ε0 is the vacuum permittivity and μ0 is the vacuum permeability. Throughout, the relation ε 0 μ 0 = 1 c 2 {\displaystyle \varepsilon _{0}\mu _{0}={\dfrac {1}{c^{2}}}} is also used. SI units E and B fields Maxwell's equations can directly give inhomogeneous wave equations for the electric field E and magnetic field B.[1] Substituting Gauss' law for electricity into the curl of Faraday's law of induction, and using the curl of the curl identity ∇ × (∇ × X) = ∇(∇ ⋅ X) − ∇2X gives the wave equation for the electric field E: 1 c 2 ∂ 2 E ∂ t 2 − ∇ 2 E = − (1 ε 0 ∇ ρ + μ 0 ∂ J ∂ t) . {\displaystyle {\dfrac {1}{c^{2}}}{\dfrac {\partial ^{2}\mathbf {E} }{\partial t^{2}}}-abla ^{2}\mathbf {E} =-\left({\dfrac {1}{\varepsilon _{0}}}abla \rho +\mu _{0}{\dfrac {\partial \mathbf {J} }{\partial t}}\right)\,.} Similarly substituting Gauss's law for magnetism into the curl of Ampère's circuital law (with Maxwell's additional time-dependent term), and using the curl of the curl identity, gives the wave equation for the magnetic field B: 1 c 2 ∂ 2 B ∂ t 2 − ∇ 2 B = μ 0 ∇ × J . {\displaystyle {\dfrac {1}{c^{2}}}{\dfrac {\partial ^{2}\mathbf {B} }{\partial t^{2}}}-abla ^{2}\mathbf {B} =\mu _{0}abla \times \mathbf {J} \,.} The left hand sides of each equation correspond to wave motion (the D'Alembert operator acting on the fields), while the right hand sides are the wave sources. The equations imply that EM waves are generated if there are gradients in charge density ρ, circulations in current density J, time-varying current density, or any mixture these. These forms of the wave equations are not often used in practice, as the source terms are inconveniently complicated. A simpler formulation more commonly encountered in the literature and used in theory use the electromagnetic potential formulation, presented next. A and φ potential fields Introducing the electric potential φ (a scalar potential) and the magnetic potential A (a vector potential) defined from the E and B fields by: E = − ∇ φ − ∂ A ∂ t , B = ∇ × A , {\displaystyle \mathbf {E} =-abla \varphi -{\partial \mathbf {A} \over \partial t}\,,\quad \mathbf {B} =abla \times \mathbf {A} \,,} the four Maxwell's equations in a vacuum with charge ρ and current J sources reduce to two equations, Gauss' law for electricity is: ∇ 2 φ + ∂ ∂ t (∇ ⋅ A) = − ρ ε 0 , {\displaystyle abla ^{2}\varphi +{{\partial } \over \partial t}\left(abla \cdot \mathbf {A} \right)=-{\rho \over \varepsilon _{0}}\,,} and the Ampère-Maxwell law is: ∇ 2 A − 1 c 2 ∂ 2 A ∂ t 2 − ∇ (1 c 2 ∂ φ ∂ t + ∇ ⋅ A) = − μ 0 J . {\displaystyle abla ^{2}\mathbf {A} -{1 \over c^{2}}{\partial ^{2}\mathbf {A} \over \partial t^{2}}-abla \left({1 \over c^{2}}{{\partial \varphi } \over {\partial t}}+abla \cdot \mathbf {A} \right)=-\mu _{0}\mathbf {J} \,.} The source terms are now much simpler, but the wave terms are less obvious. Since the potentials are not unique, but have gauge freedom, these equations can be simplified by gauge fixing. A common choice is the Lorenz gauge condition: 1 c 2 ∂ φ ∂ t + ∇ ⋅ A = 0 {\displaystyle {1 \over c^{2}}{{\partial \varphi } \over {\partial t}}+abla \cdot \mathbf {A} =0} Then the nonhomogeneous wave equations become uncoupled and symmetric in the potentials: ∇ 2 φ − 1 c 2 ∂ 2 φ ∂ t 2 = − ρ ε 0 , {\displaystyle abla ^{2}\varphi -{1 \over c^{2}}{\partial ^{2}\varphi \over \partial t^{2}}=-{\rho \over \varepsilon _{0}}\,,} ∇ 2 A − 1 c 2 ∂ 2 A ∂ t 2 = − μ 0 J . {\displaystyle abla ^{2}\mathbf {A} -{1 \over c^{2}}{\partial ^{2}\mathbf {A} \over \partial t^{2}}=-\mu _{0}\mathbf {J} \,.} For reference, in cgs units these equations are ∇ 2 φ − 1 c 2 ∂ 2 φ ∂ t 2 = − 4 π ρ {\displaystyle abla ^{2}\varphi -{1 \over c^{2}}{\partial ^{2}\varphi \over \partial t^{2}}=-{4\pi \rho }} ∇ 2 A − 1 c 2 ∂ 2 A ∂ t 2 = − 4 π c J {\displaystyle abla ^{2}\mathbf {A} -{1 \over c^{2}}{\partial ^{2}\mathbf {A} \over \partial t^{2}}=-{4\pi \over c}\mathbf {J} } with the Lorenz gauge condition 1 c 2 ∂ φ ∂ t + ∇ ⋅ A = 0 . {\displaystyle {1 \over c^{2}}{{\partial \varphi } \over {\partial t}}+abla \cdot \mathbf {A} =0\,.} Covariant form of the inhomogeneous wave equation See also: Covariant formulation of classical electromagnetism Time dilation in transversal motion. The requirement that the speed of light is constant in every inertial reference frame leads to the theory of relativity The relativistic Maxwell's equations can be written in covariant form as ◻ A μ = d e f ∂ β ∂ β A μ = d e f A μ , β β = − μ 0 J μ SI {\displaystyle \Box A^{\mu }\ {\stackrel {\mathrm {def} }{=}}\ \partial _{\beta }\partial ^{\beta }A^{\mu }\ {\stackrel {\mathrm {def} }{=}}\ {A^{\mu ,\beta }}_{\beta }=-\mu _{0}J^{\mu }\quad {\text{SI}}}} ◻ A μ = d e f ∂ β ∂ β A μ = d e f A μ , β β = − 4 π c J μ cgs {\displaystyle \Box A^{\mu }\ {\stackrel {\mathrm {def} }{=}}\ \partial _{\beta }\partial ^{\beta }A^{\mu }\ {\stackrel {\mathrm {def} }{=}}\ {A^{\mu ,\beta }}_{\beta }=-{\frac {4\pi }{c}}J^{\mu }\quad {\text{cgs}}}} where ◻ = ∂ β ∂ β = ∇ 2 − 1 c 2 ∂ 2 ∂ t 2 {\displaystyle \Box =\partial _{\beta }\partial ^{\beta }=abla ^{2}-{1 \over c^{2}}{\frac {\partial ^{2}}{\partial t^{2}}}} is the d'Alembert operator, J μ = (c ρ , J) {\displaystyle J^{\mu }=\left(c\rho ,\mathbf {J} \right)} is the four-current, ∂ ∂ x a = d e f ∂ a = d e f , a = d e f (∂ / ∂ c t , ∇) {\displaystyle {\partial \over {\partial x^{a}}}\ {\stackrel {\mathrm {def} }{=}}\ \partial _{a}\ {\stackrel {\mathrm {def} }{=}}\ {}_{,a}\ {\stackrel {\mathrm {def} }{=}}\ (\partial /\partial ct,abla)} is the 4-gradient, and A μ = (φ / c , A) SI {\displaystyle A^{\mu }=(\varphi /c,\mathbf {A})\quad {\text{SI}}}} A μ = (φ , A) cgs {\displaystyle A^{\mu }=(\varphi ,\mathbf {A})\quad {\text{cgs}}}} is the electromagnetic four-potential with the Lorenz gauge condition ∂ μ A μ = 0 . {\displaystyle \partial _{\mu }A^{\mu }=0\,.} Curved spacetime The electromagnetic wave equation is modified in two ways in curved spacetime, the derivative is replaced with the covariant derivative and a new term that depends on the curvature appears (SI units). − A α ; β β + R α β A β = μ 0 J α {\displaystyle -{A^{\alpha ;\beta }}_{\beta }+{R^{\alpha }}_{\beta }A^{\beta }=\mu _{0}J^{\alpha }} where R α β {\displaystyle {R^{\alpha }}_{\beta }} is the Ricci curvature tensor. Here the semicolon indicates covariant differentiation. To obtain the equation in cgs units, replace the permeability with 4π/c. The Lorenz gauge condition in curved spacetime is assumed: A μ ; μ = 0 . {\displaystyle {A^{\mu }}_{;\mu }=0\,.} Solutions to the inhomogeneous electromagnetic wave equation Retarded spherical wave. The source of the wave occurs at time t'. The wavefront moves away from the source as time increases for t > t'. For advanced solutions, the wavefront moves backwards in time from the source t < t'. In the case that there are no boundaries surrounding the sources, the solutions (cgs units) of the nonhomogeneous wave equations are φ (r , t) = ∫ δ (t ′ + | r − r ′ | c − t) | r − r ′ | ρ (r ′ , t ′) d 3 r ′ d t ′ {\displaystyle \varphi (\mathbf {r} ,t)=\int {{\delta \left(t'+{{\left|\mathbf {r} -\mathbf {r} '\right|} \over c}-t\right)} \over {\left|\mathbf {r} -\mathbf {r} '\right|}}\rho (\mathbf {r} ',t')d^{3}r'dt'} and A (r , t) = ∫ δ (t ′ + | r − r ′ | c − t) | r − r ′ | J (r ′ , t ′) c d 3 r ′ d t ′ {\displaystyle \mathbf {A} (\mathbf {r} ,t)=\int {{\delta \left(t'+{{\left|\mathbf {r} -\mathbf {r} '\right|} \over c}-t\right)} \over {\left|\mathbf {r} -\mathbf {r} '\right|}}{\mathbf {J} (\mathbf {r} ',t') \over c}d^{3}r'dt'} where δ (t ′ + | r − r ′ | c − t) {\displaystyle {\delta \left(t'+{{\left|\mathbf {r} -\mathbf {r} '\right|} \over c}-t\right)}} is a Dirac delta function. These solutions are known as the retarded Lorenz gauge potentials. They represent a superposition of spherical light waves traveling outward from the sources of the waves, from the present into the future. There are also advanced solutions (cgs units) φ (r , t) = ∫ δ (t ′ − | r − r ′ | c − t) | r − r ′ | ρ (r ′ , t ′) d 3 r ′ d t ′ {\displaystyle \varphi (\mathbf {r} ,t)=\int {{\delta \left(t'-{{\left|\mathbf {r} -\mathbf {r} '\right|} \over c}-t\right)} \over {\left|\mathbf {r} -\mathbf {r} '\right|}}\rho (\mathbf {r} ',t')d^{3}r'dt'} and A (r , t) = ∫ δ (t ′ − | r − r ′ | c − t) | r − r ′ | J (r ′ , t ′) c d 3 r ′ d t ′ . {\displaystyle \mathbf {A} (\mathbf {r} ,t)=\int {{\delta \left(t'-{{\left|\mathbf {r} -\mathbf {r} '\right|} \over c}-t\right)} \over {\left|\mathbf {r} -\mathbf {r} '\right|}}{\mathbf {J} (\mathbf {r} ',t') \over c}d^{3}r'dt'\,.} These represent a superposition of spherical waves travelling from the future into the present. See also Wave equation Sinusoidal plane-wave solutions of the electromagnetic wave equation Larmor formula Formulation of Maxwell's equations in special relativity Maxwell's equations in curved spacetime Abraham–Lorentz force Green's function References ^ Classical electrodynamics, Jackson, 3rd edition, p. 246 Electromagnetics Journal articles James Clerk Maxwell, "A Dynamical Theory of the Electromagnetic Field", Philosophical Transactions of the Royal Society of London 155, 459-512 (1865). (This article accompanied a December 8, 1864 presentation by Maxwell to the Royal Society.) Undergraduate-level textbooks Griffiths, David J. (1998). Introduction to Electrodynamics (3rd ed.). Prentice Hall. ISBN 0-13-805326-X. Tipler, Paul (2004). Physics for Scientists and Engineers: Electricity, Magnetism, Light, and Elementary Modern Physics (5th ed.). W. H. Freeman. ISBN 0-7167-0810-8. Edward M. Purcell, Electricity and Magnetism (McGraw-Hill, New York, 1985). Hermann A. Haus and James R. 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