Elektromagnetische Feldtheorie I (EFT I) / Electromagnetic Field Theory I (EFT I)

2nd Lecture / 2. Vorlesung

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Notation and Field Quantities / Notation und Feldgrößen

Vector / Vektor:
Electric Field Strength / Elektrische Feldstärke

$$\underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \underbrace{\underline{\mathbf{E}}_x(\underline{\mathbf{R}},t) + \underline{\mathbf{E}}_y(\underline{\mathbf{R}},t) + \underline{\mathbf{E}}_z(\underline{\mathbf{R}},t)}_{\text{3 Vector Components / 3 Vektorkomponenten}}$$

$$= \mathrm{E}_x(x,y,z,t)\underline{\mathbf{e}}_x + \mathrm{E}_y(x,y,z,t)\underline{\mathbf{e}}_y + \mathrm{E}_z(x,y,z,t)\underline{\mathbf{e}}_z$$

mit $\{x,y,z\} = \{x_1,x_2,x_3\}$

$$= \sum_{i=1}^{3} \mathrm{E}_{x_i}(x_1,x_2,x_3,t)\underline{\mathbf{e}}_{x_i}$$

$$= \mathrm{E}_{x_i}(x_1,x_2,x_3,t)\underline{\mathbf{e}}_{x_i}$$

Dyad / Dyade:
Permittivity Dyad / Permittivitätsdyade

$$\underline{\underline{\varepsilon}}(\underline{\mathbf{R}},t) = \underline{\underline{\varepsilon}}_{xx}(\underline{\mathbf{R}},t) + \underline{\underline{\varepsilon}}_{xy}(\underline{\mathbf{R}},t) + \underline{\underline{\varepsilon}}_{xz}(\underline{\mathbf{R}},t)$$
$$+ \underline{\underline{\varepsilon}}_{yx}(\underline{\mathbf{R}},t) + \underline{\underline{\varepsilon}}_{yy}(\underline{\mathbf{R}},t) + \underline{\underline{\varepsilon}}_{yz}(\underline{\mathbf{R}},t)$$
$$\underbrace{+ \underline{\underline{\varepsilon}}_{zx}(\underline{\mathbf{R}},t) + \underline{\underline{\varepsilon}}_{zy}(\underline{\mathbf{R}},t) + \underline{\underline{\varepsilon}}_{zz}(\underline{\mathbf{R}},t)}_{\text{9 Dyadic Components / 9 dyadische Komponenten}}$$

$$= \varepsilon_{xx}(x,y,z,t)\underline{\mathbf{e}}_x\underline{\mathbf{e}}_x + \varepsilon_{xy}(x,y,z,t)\underline{\mathbf{e}}_x\underline{\mathbf{e}}_y + \varepsilon_{xz}(x,y,z,t)\underline{\mathbf{e}}_x\underline{\mathbf{e}}_z$$
$$+ \varepsilon_{yx}(x,y,z,t)\underline{\mathbf{e}}_y\underline{\mathbf{e}}_x + \varepsilon_{yy}(x,y,z,t)\underline{\mathbf{e}}_y\underline{\mathbf{e}}_y + \varepsilon_{yz}(x,y,z,t)\underline{\mathbf{e}}_y\underline{\mathbf{e}}_z$$
$$+ \varepsilon_{zx}(x,y,z,t)\underline{\mathbf{e}}_z\underline{\mathbf{e}}_x + \varepsilon_{zy}(x,y,z,t)\underline{\mathbf{e}}_z\underline{\mathbf{e}}_y + \varepsilon_{zz}(x,y,z,t)\underline{\mathbf{e}}_z\underline{\mathbf{e}}_z$$

mit $\{x,y,z\} = \{x_1,x_2,x_3\}$

$$= \sum_{i=1}^{3}\sum_{j=1}^{3} \varepsilon_{x_i x_j}(x_1,x_2,x_3,t)\underline{\mathbf{e}}_{x_i}\underline{\mathbf{e}}_{x_j}$$

$$= \varepsilon_{x_i x_j}(x_1,x_2,x_3,t)\underline{\mathbf{e}}_{x_i}\underline{\mathbf{e}}_{x_j}$$

with Einstein's Summation Convention / mit Einsteinscher Summationskonvention

Einstein's Summation Convention: If a index appears two times at one side of an equation (and not at the other side), the index is automatically summed over 1 to 3. / *Einsteinsche Summenkonvention*: Wenn ein Index auf einer Seite einer Gleichung zweimal vorkommt (und auf der anderen nicht), wird darüber von 1 bis 3 summiert.

Governing Equations of Electromagnetic Fields and Waves / Grundgleichungen elektromagnetischer Felder und Wellen

Governing Equations in Differential Form / Grundgleichungen in Differentialform

$$\nabla \times \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = -\frac{\partial}{\partial t}\underline{\mathbf{B}}(\underline{\mathbf{R}},t) - \underline{\mathbf{J}}_{\mathrm{m}}(\underline{\mathbf{R}},t)$$

$$\nabla \times \underline{\mathbf{H}}(\underline{\mathbf{R}},t) = \frac{\partial}{\partial t}\underline{\mathbf{D}}(\underline{\mathbf{R}},t) + \underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t)$$

$$\nabla \bullet \underline{\mathbf{D}}(\underline{\mathbf{R}},t) = \rho_{\mathrm{e}}(\underline{\mathbf{R}},t)$$

$$\nabla \bullet \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \rho_{\mathrm{m}}(\underline{\mathbf{R}},t)$$

$$\nabla \bullet \underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t) = -\frac{\partial}{\partial t}\rho_{\mathrm{e}}(\underline{\mathbf{R}},t)$$

$$\nabla \bullet \underline{\mathbf{J}}_{\mathrm{m}}(\underline{\mathbf{R}},t) = -\frac{\partial}{\partial t}\rho_{\mathrm{m}}(\underline{\mathbf{R}},t)$$

Governing Equations in Integral Form / Grundgleichungen in Integralform

$$\oint_{C=\partial S} \underline{\mathbf{E}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dR}} = -\iint_S \frac{\partial}{\partial t}\underline{\mathbf{B}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dS}} - \iint_S \underline{\mathbf{J}}_{\mathrm{m}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dS}}$$

$$\oint_{C=\partial S} \underline{\mathbf{H}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dR}} = \iint_S \frac{\partial}{\partial t}\underline{\mathbf{D}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dS}} + \iint_S \underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dS}}$$

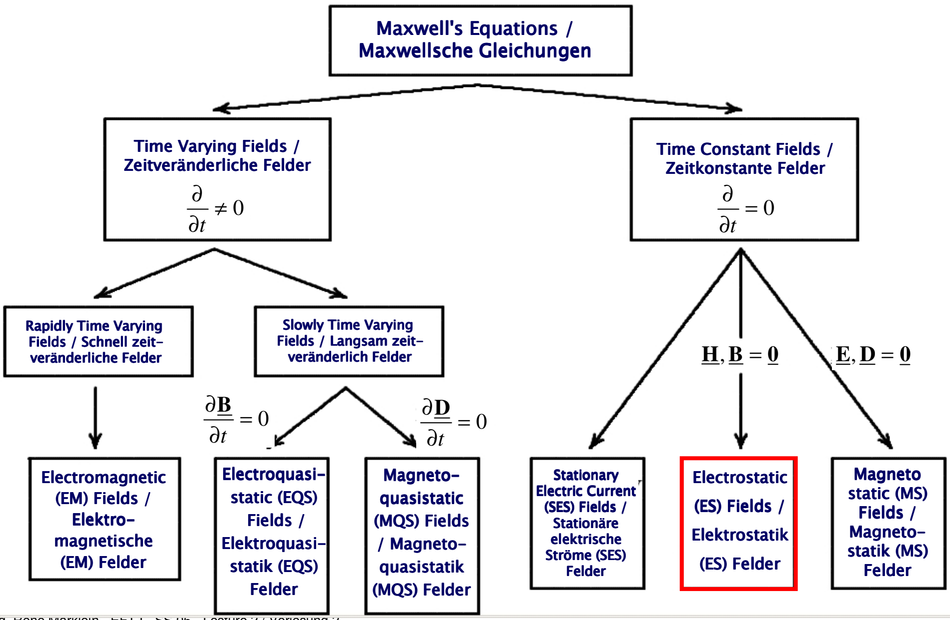
$$\oiint_{S=\partial V} \underline{\mathbf{D}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dS}} = \iiint_V \rho_{\mathrm{e}}(\underline{\mathbf{R}},t)\,\mathrm{d}V$$

$$\oiint_{S=\partial V} \underline{\mathbf{B}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dS}} = \iiint_V \rho_{\mathrm{m}}(\underline{\mathbf{R}},t)\,\mathrm{d}V$$

$$\oiint_{S=\partial V} \underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dS}} = -\iiint_V \frac{\partial}{\partial t}\rho_{\mathrm{e}}(\underline{\mathbf{R}},t)\,\mathrm{d}V$$

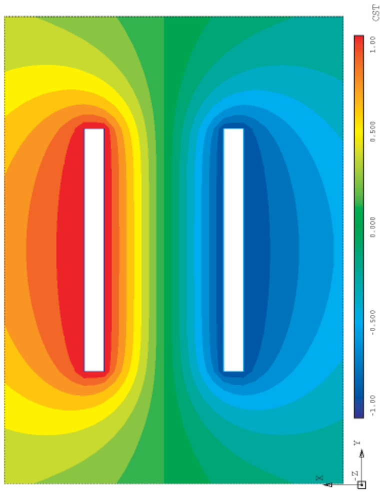
$$\oiint_{S=\partial V} \underline{\mathbf{J}}_{\mathrm{m}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dS}} = -\iiint_V \frac{\partial}{\partial t}\rho_{\mathrm{m}}(\underline{\mathbf{R}},t)\,\mathrm{d}V$$

Classification of Maxwell‘s Equations / Klassifikation der Maxwellschen Gleichungen

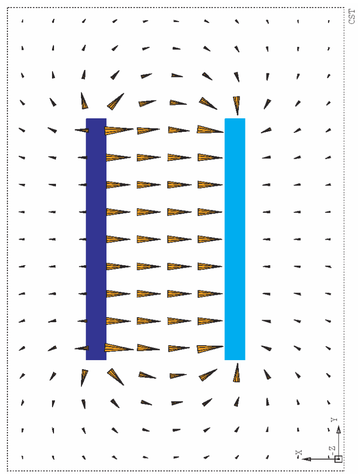


Electrostatic Field Problem – Example: Parallel Plate Capacitor / Elektrostatisches Feldproblem – Beispiel: Paralleler Plattenkondensator

Scalar Field: Electrostatic Potential / Skalarfeld: Elektrostatisches Potenzial

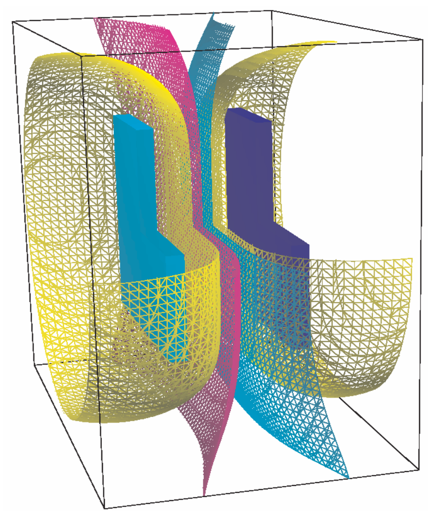


Vector Field: Electrostatic Field Strength / Vektorfeld: Elektrostatische Feldstärke

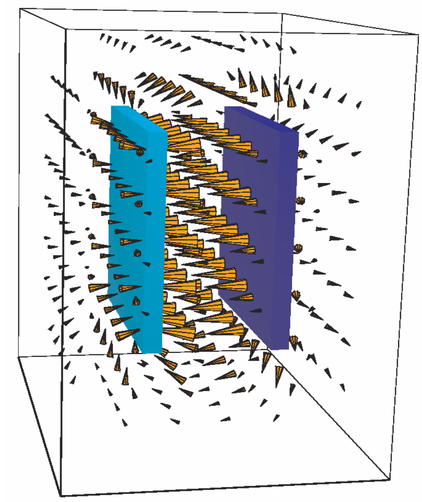


Example: Parallel Plate Capacitor – Electrostatic Field Problem / Beispiel: Paralleler Plattenkondensator – Elektrostatisches Feldproblem

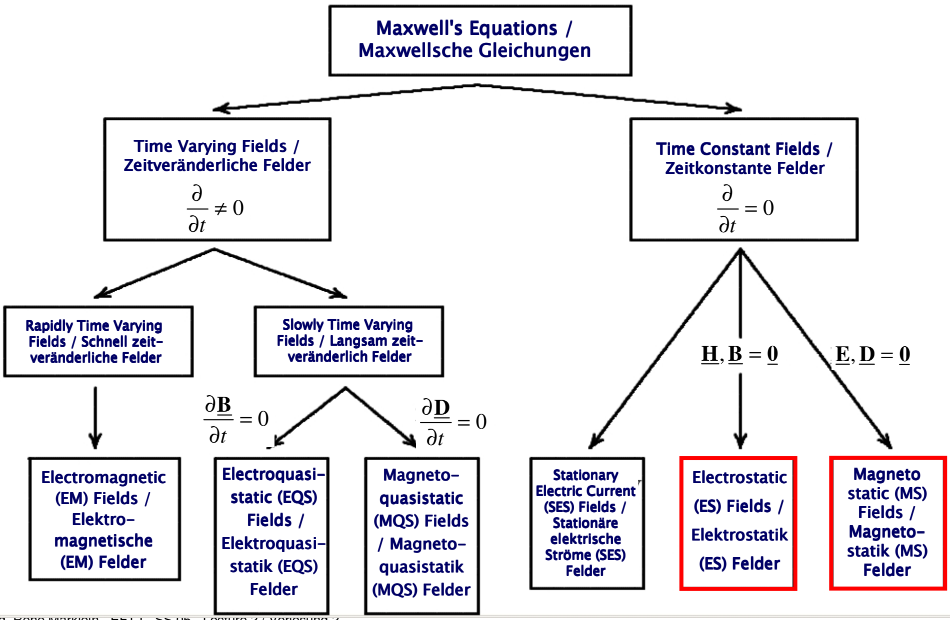
Scalar Field: Electrostatic Potential / Skalarfeld: Elektrostatisches Potenzial



Vector Field: Electrostatic Field Strength / Vektorfeld: Elektrostatische Feldstärke



Classification of Maxwell's Equations / Klassifikation der Maxwellschen Gleichungen

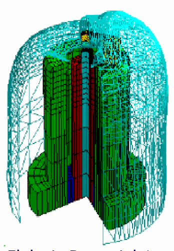


Example: Spark Plug and Relay / Beispiel: Zündkerze und Relais

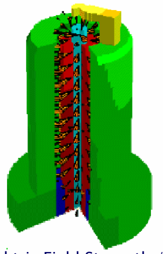
Electrostatic (ES) Fields / Elektrostatische (ES) Felder

Spark Plug / Zündkerze

Elektric Field Strength / Elektrische Feldstärke



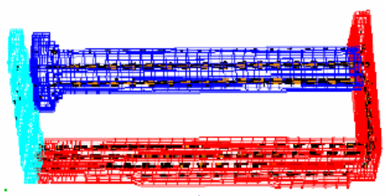
Elektric Potential / Elektrisches Potenzial



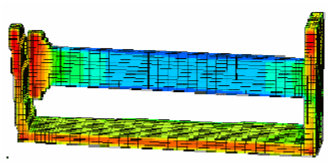
Elektric Field Strength / Elektrische Feldstärke

Magnetostatic (MS) Fields / Magnetostatische (MS) Felder

Relay / Relais

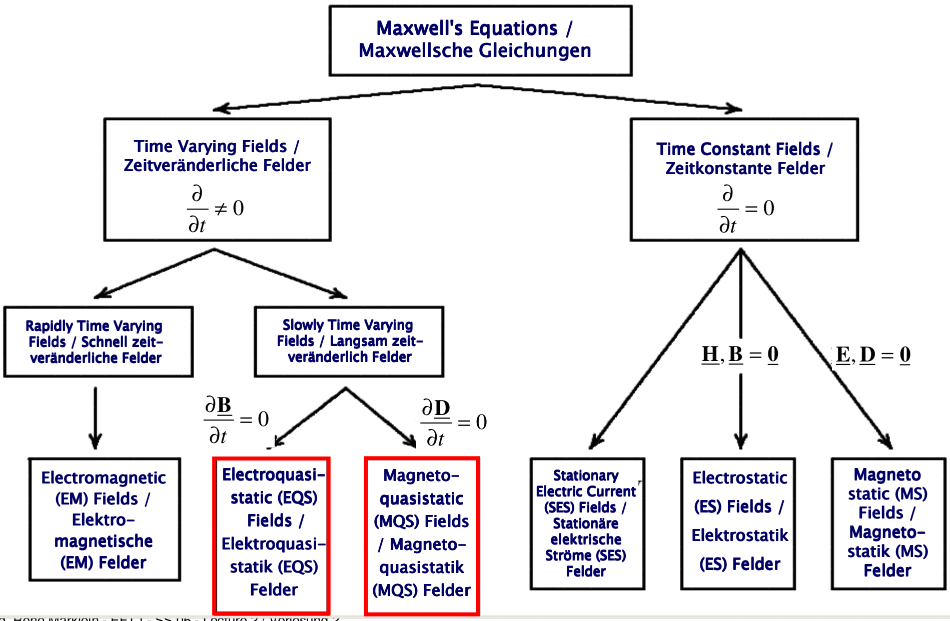


Magnetic Flux Density / Magnetische Flussdichte



Permeability / Permeabilität

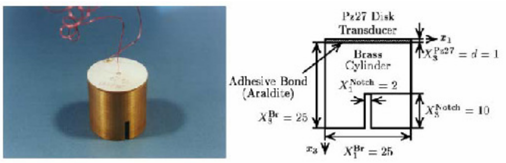
Classification of Maxwell's Equations / Klassifikation der Maxwellschen Gleichungen

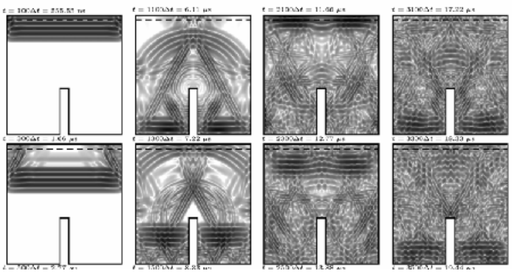


Example: Piezoelectric Sensor / Beispiel: Piezoelektrischer Sensor

Electroquasistatic (EQS) Fields / Elektroquasistatische (EQS) Felder

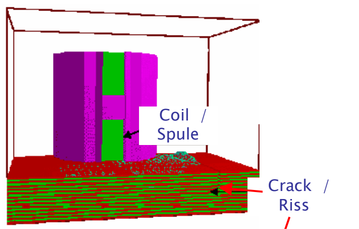
Non-Destructive Testing: Piezoelectric Sensor /
Zerstörungsfreie Materialprüfung: Piezoelektrischer Sensor



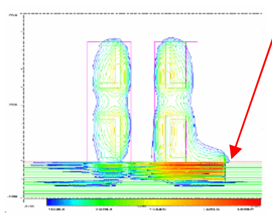


Magnetoquasistatic (MQS) Fields / Magnetoquasistatische (MQS) Felder

Non-Destructive Testing: Eddy Current Sensor /
Zerstörungsfreie Materialprüfung: Wirbelstromsensor



Geometry / Geometrie



Electric Energy Density / Elektrische Energiedichte

Classification of Maxwell‘s Equations / Klassifikation der Maxwellschen Gleichungen

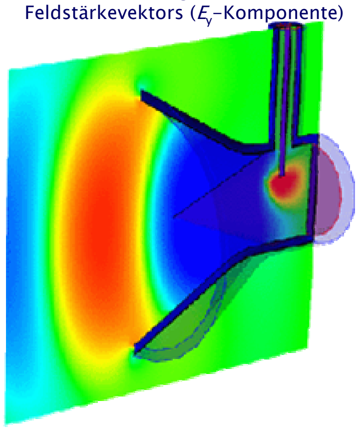
Maxwell's Equations / Maxwellsche Gleichungen

- **Time Varying Fields / Zeitveränderliche Felder** $\frac{\partial}{\partial t} \neq 0$
  - **Rapidly Time Varying Fields / Schnell zeit-veränderliche Felder**
    - **Electromagnetic (EM) Fields / Elektro-magnetische (EM) Felder**
  - **Slowly Time Varying Fields / Langsam zeit-veränderlich Felder**
    - $\frac{\partial \underline{\mathbf{B}}}{\partial t} = 0$: **Electroquasi-static (EQS) Fields / Elektroquasi-statik (EQS) Felder**
    - $\frac{\partial \underline{\mathbf{D}}}{\partial t} = 0$: **Magneto-quasistatic (MQS) Fields / Magneto-quasistatik (MQS) Felder**
- **Time Constant Fields / Zeitkonstante Felder** $\frac{\partial}{\partial t} = 0$
  - **Stationary Electric Current (SES) Fields / Stationäre elektrische Ströme (SES) Felder**
  - $\underline{\mathbf{H}}, \underline{\mathbf{B}} = \underline{\mathbf{0}}$: **Electrostatic (ES) Fields / Elektrostatik (ES) Felder**
  - $\underline{\mathbf{E}}, \underline{\mathbf{D}} = \underline{\mathbf{0}}$: **Magneto static (MS) Fields / Magneto-statik (MS) Felder**

Examples: Antenna and Human Head Interaction / Beispiele: Antenne und Interaktion mit menschlichem Kopf

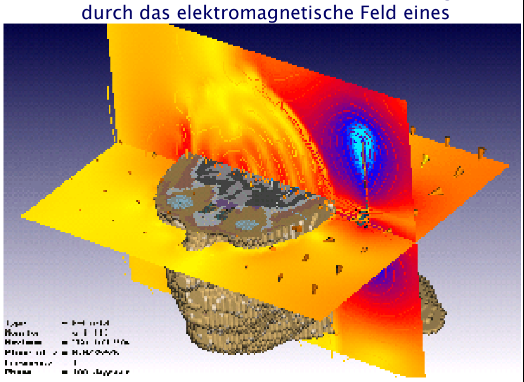
Rapidly Time Varying Electromagnetic (EM) Fields / Zeitlich schnell veränderliche elektromagnetische (EM) Felder

Horn Antenna: Contour Plot of Electric Field Strength Vector (E_y Component) / Hornantenne: Konturdarstellung des elektrischen Feldstärkevektors (E_y-Komponente)



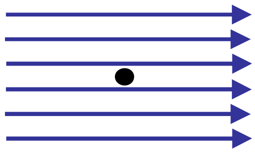
(CST Microwave Studio, www.cst.de)

Biomedical Application: Human head model irradiated by the electromagnetic field of a mobile phone / Biomedizinische Anwendung: Menschliches Kopfmodell bei Bestrahlung durch das elektromagnetische Feld eines



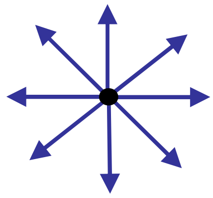
(CST Microwave Studio, www.cst.de)

Examples: Div and Curl / Beispiele: Div und Rot



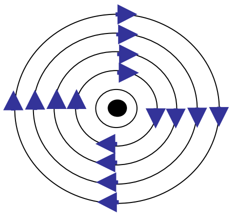
$$\operatorname{div}\,\underline{\mathbf{A}} = \nabla \bullet \underline{\mathbf{A}} = 0$$

$$\operatorname{curl}/\operatorname{rot}\,\underline{\mathbf{A}} = \nabla \times \underline{\mathbf{A}} = \underline{\mathbf{0}}$$



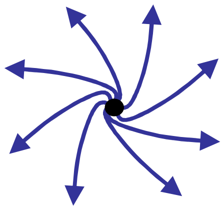
$$\operatorname{div}\,\underline{\mathbf{A}} = \nabla \bullet \underline{\mathbf{A}} \neq 0$$

$$\operatorname{curl}/\operatorname{rot}\,\underline{\mathbf{A}} = \nabla \times \underline{\mathbf{A}} = \underline{\mathbf{0}}$$



$$\operatorname{div}\,\underline{\mathbf{A}} = \nabla \bullet \underline{\mathbf{A}} = 0$$

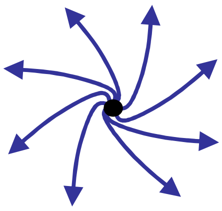
$$\operatorname{curl}/\operatorname{rot}\,\underline{\mathbf{A}} = \nabla \times \underline{\mathbf{A}} \neq \underline{\mathbf{0}}$$



$$\operatorname{div}\,\underline{\mathbf{A}} = \nabla \bullet \underline{\mathbf{A}} \neq 0$$

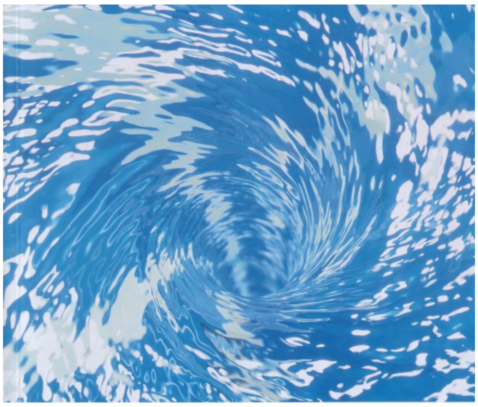
$$\operatorname{curl}/\operatorname{rot}\,\underline{\mathbf{A}} = \nabla \times \underline{\mathbf{A}} \neq \underline{\mathbf{0}}$$

Examples: Div and Curl / Beispiele: Div und Rot



$$\operatorname{div}\,\underline{\mathbf{A}} = \nabla \bullet \underline{\mathbf{A}} \neq 0$$

$$\operatorname{curl}/\operatorname{rot}\,\underline{\mathbf{A}} = \nabla \times \underline{\mathbf{A}} \neq \underline{\mathbf{0}}$$



Grad, Div and Curl Examples / Grad, Div und Rot Beispiele

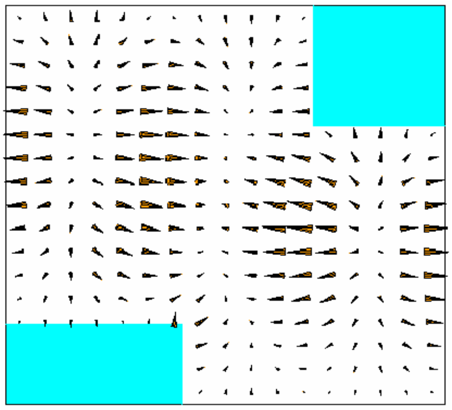
Vector Field / Vektorfeld

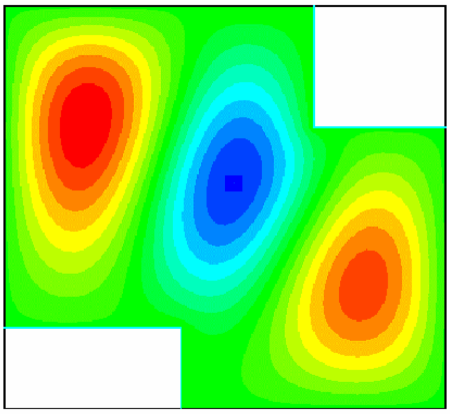
$\underline{\mathbf{D}}(\underline{\mathbf{R}})$

Scalar Field / Skalarfeld

$\rho_e(\underline{\mathbf{R}}) = \operatorname{div} \underline{\mathbf{D}}(\underline{\mathbf{R}}) = \nabla \cdot \underline{\mathbf{D}}(\underline{\mathbf{R}})$

$$\operatorname{div} \underline{\mathbf{D}}(\underline{\mathbf{R}}) = \nabla \cdot \underline{\mathbf{D}}(\underline{\mathbf{R}}) = \frac{\partial}{\partial x} \mathrm{D}_x(x,y,z) + \frac{\partial}{\partial y} \mathrm{D}_y(x,y,z) + \frac{\partial}{\partial z} \mathrm{D}_z(x,y,z)$$





Grad, Div and Curl Examples / Grad, Div und Rot Beispiele

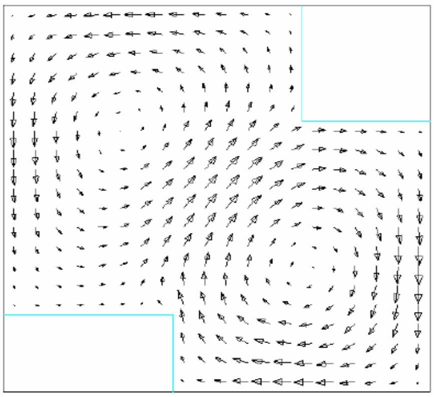
Vector Field / Vektorfeld

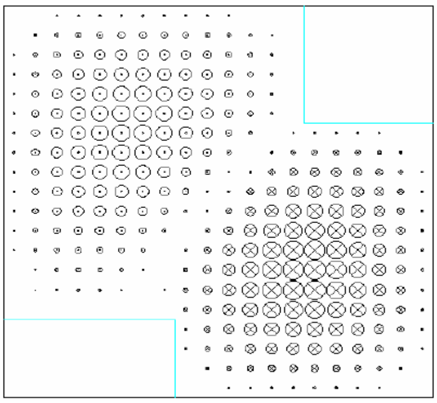
$\underline{\mathbf{E}}(\underline{\mathbf{R}},t)$

Vector Field / Vektorfeld

$\text{curl/rot}\, \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \nabla \times \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = -\frac{\partial}{\partial t} \underline{\mathbf{B}}(\underline{\mathbf{R}},t)$

$$\text{curl / rot}\, \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \nabla \times \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \left(\underline{\mathbf{e}}_x \frac{\partial}{\partial x} + \underline{\mathbf{e}}_y \frac{\partial}{\partial y} + \underline{\mathbf{e}}_z \frac{\partial}{\partial z} \right) \times \underline{\mathbf{E}}(x,y,z,t)$$





Hertzian Dipole Antenna in Free-Space / Hertzsche Dipolantenne im Freiraum (1)

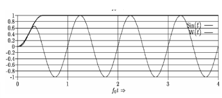
Excitation: Point-like Transient Electric Current Density / Anregung: Punktförmige transiente elektrische Stromdichte

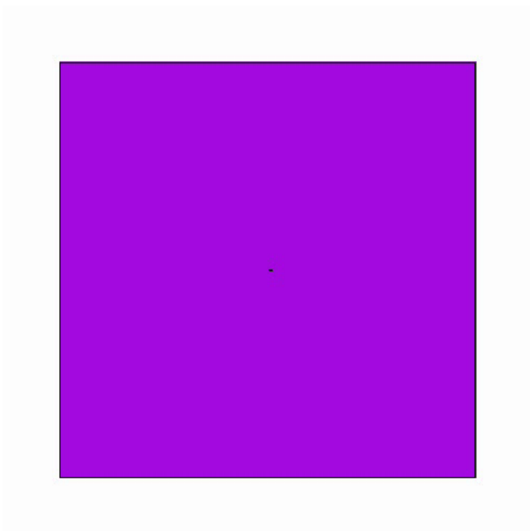
$$\underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t)=\begin{cases}0 & t<0\\ I_0\sin\left(\omega_0 t\right)\,\delta(\underline{\mathbf{R}})\,\underline{\mathbf{e}}_z & t\geq 0\end{cases}$$

$$\underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t)\sim I_0\sin\left(\omega_0 t\right)\underline{\mathbf{e}}_z$$

Hertzian Dipole Antenna in Free-Space / Hertzsche Dipolantenne im Freiraum (2)

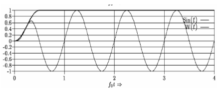
Monofrequent/Monochromatic Excitation / Monofrequente/Monochromatische Anregung $\mathrm{J}_{\mathrm{e}z}(\underline{\mathbf{R}},t)\sim\sin\left(\omega_0 t\right)$

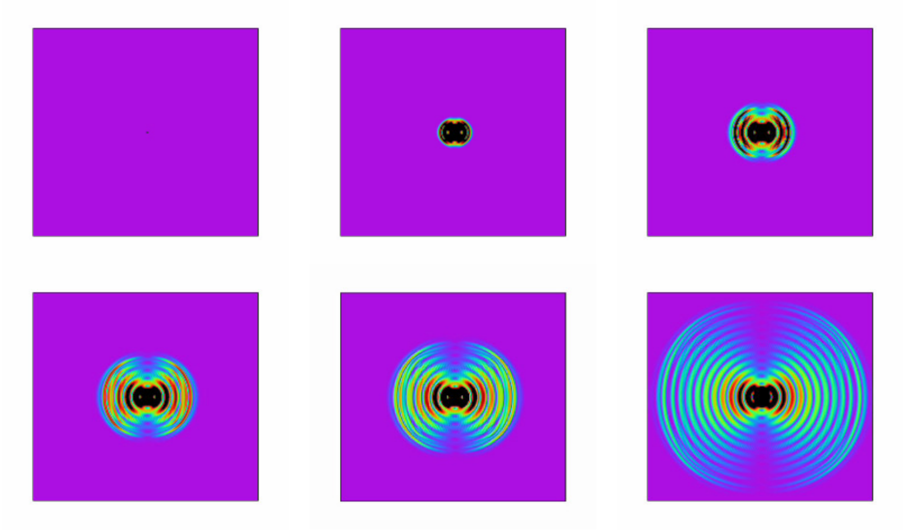




Hertzian Dipole Antenna in Free-Space / Hertzsche Dipolantenne im Freiraum (3)

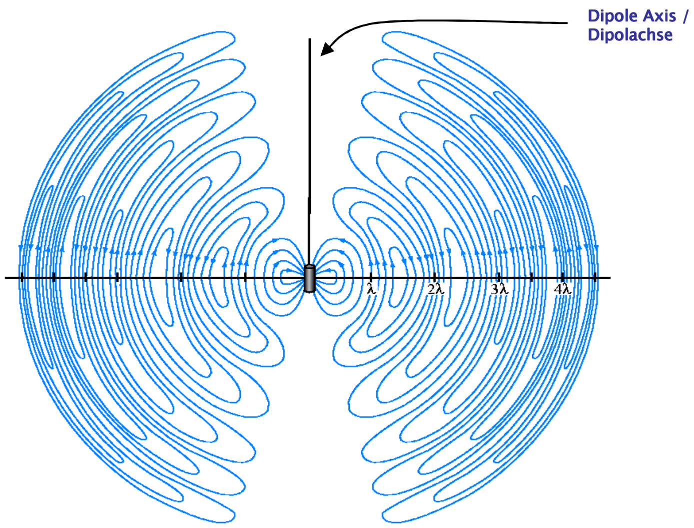
Monofrequent/Monochromatic Excitation / Monofrequente/Monochromatische Anregung $\mathrm{J}_{ez}(\underline{\mathbf{R}}, t) \sim \sin(\omega_0 t)$





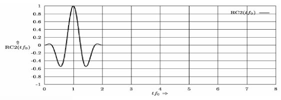
Hertzian Dipole Antenna in Free-Space / Hertzsche Dipolantenne im Freiraum (4)

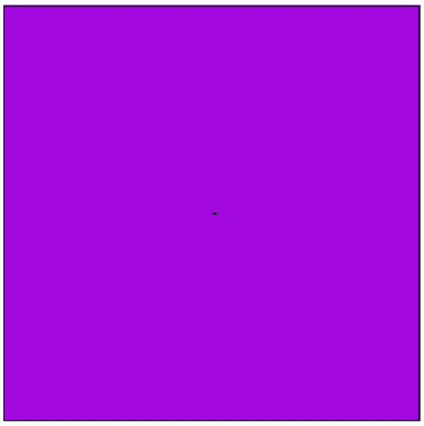
Electric Field Lines Surrounding an Oscillating Dipole at a Given Instant / Elektrische Feldlinien, die einen oszillierenden Dipol zu einem festen Zeitpunkt umgeben



Hertzian Dipole Antenna in Free-Space / Hertzsche Dipolantenne im Freiraum (5)

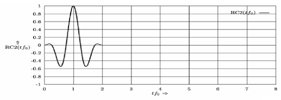
Broadband Pulse Excitation / Breitbandige Impulsanregung: $J_{ez}(\underline{\mathbf{R}}, t) \sim RC_2(t)$

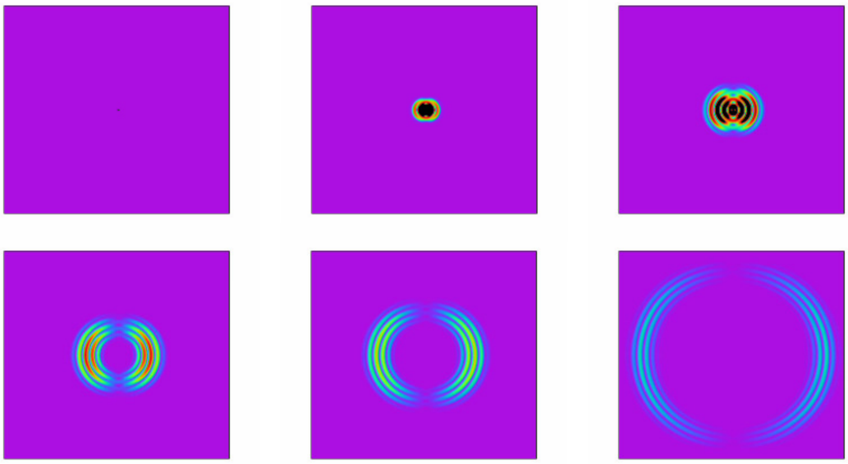




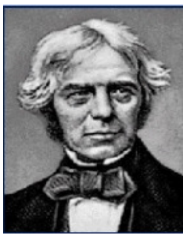
Hertzian Dipole Antenna in Free-Space / Hertzsche Dipolantenne im Freiraum (6)

Broadband Pulse Excitation / Breitbandige Impulsanregung: $J_{ez}(\underline{\mathbf{R}}, t) \sim RC_2(t)$





Maxwell‘s Equations / Maxwellsche Gleichungen

1.  2.  3.  4. 

1. **André Marie Ampère (1775-1836)** **1827: Ampère presented the first mathematical theory of electrodynamics and discovered the magnetic effect of electric currents. / Ampère stellte die erste mathematisch fundierte elektrodynamische Theorie vor und entdeckte die magnetische Wirkung elektrischer Ströme.**

2. **Michael Faraday (1791-1867)** **1831: Faraday discovers electromagnetic induction. / Faraday entdeckt die elektromagnetische Induktion.**

3. **James Clerk Maxwell (1831-1879)** **1864: Maxwell presents his theory of electromagnetism. / Maxwell präsentiert seine Theorie des Elektromagnetismus.**

4. **Heinrich Rudolf Hertz (1857-1894)** **1885: Hertz demonstrates the electromagnetic wave propagation in a series of experiments in a period through 1887. / Hertz demonstriert in einer Periode bis 1887 die Ausbreitung von elektromagnetischen Wellen.**

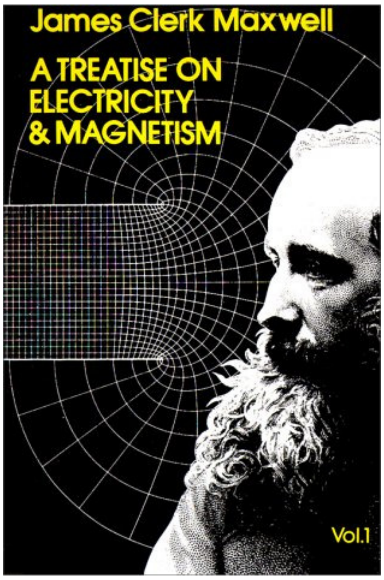
Heinrich Rudolf Hertz

Heinrich Rudolf Hertz (* 22. Februar 1857 in Hamburg, † 1. Januar 1894 in Bonn) war ein deutscher Physiker.

Er studierte an der Universität Berlin. Von 1885 bis 1889 lehrte er als Professor für Physik an der technischen Hochschule in Karlsruhe. Ab 1889 war er Professor für Physik an der Universität in Bonn. Sein Hauptverdienst lag im experimentellen Nachweis von James Clerk Maxwells elektromagnetischer Theorie des Lichts von 1884. Hertz entdeckte in Karlsruhe die Existenz der elektromagnetischen Wellen. Er wies nach, dass sie sich auf die gleiche Art und mit der gleichen Geschwindigkeit ausbreiten wie Lichtwellen (siehe: Brechung, Polarisation und Reflexion). Seine Ergebnisse lieferten die Grundlage für die Entwicklung der drahtlosen Telegraphie und des Radios. Die Einheit der Frequenz, eine Schwingung pro Sekunde = 1 Hertz (Abk. 1 Hz), ist nach ihm benannt und seit 1933 im internationalen metrischen System verankert. Ebenfalls wurde der Hamburger Fernsehturm (*Heinrich-Hertz-Turm*) und das zur Fraunhofer-Gesellschaft gehörige Berliner Heinrich-Hertz-Institut nach ihm benannt.

Heinrich Rudolf Hertz (February 22, 1857 - January 1, 1894), was the German physicist for whom the hertz, the SI unit of frequency, is named. In 1888, he was the first to demonstrate the existence of electromagnetic radiation by building apparatus to produce radio waves. Hertz was born in Hamburg, Germany, to a Jewish family that had converted to Christianity. His father was an advocate in Hamburg, his mother the daughter of a doctor. While at school, he showed an aptitude for sciences as well as languages, learning Arabic and Sanskrit. He studied sciences and engineering in the German cities of Dresden, Munich and Berlin. He was a student of Gustav R. Kirchhoff and Hermann von Helmholtz. He obtained his PhD in 1880, and remained a pupil of Helmholtz until 1883 when he took a post as a lecturer in theoretical physics at the University of Kiel. In 1885 he became a full professor at the University of Karlsruhe where he discovered electromagnetic waves. Following Michelson's 1881 experiment (precursor to the 1887 Michelson-Morley experiment) which disproved the existence of luminiferous aether, he reformulated Maxwell's equations to take the new discovery into account. Through experimentation, he proved that electric signals can travel through open air, as had been predicted by James Clerk Maxwell and Michael Faraday, and which is the basis for the invention of radio. He also discovered the photoelectric effect (which was later explained by Albert Einstein) when he noticed that a charged object loses its charge more readily when illuminated by ultraviolet light. He died in Bonn, Germany. His nephew Gustav Ludwig Hertz was a Nobel Prize winner, and Gustav's son Carl Hellmuth Hertz invented medical ultrasonography.

Maxwell's Equations / Maxwellsche Gleichungen



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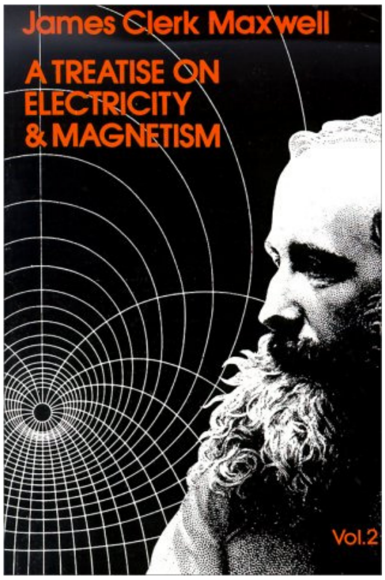

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Today's Vector Notation of Maxwell's Equations / Heutige Vektornotation der Maxwellschen Gleichungen

Governing Equations in Differential Form / Grundgleichungen in Differentialform

$$\nabla \times \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = -\frac{\partial}{\partial t}\underline{\mathbf{B}}(\underline{\mathbf{R}},t) - \underline{\mathbf{J}}_{\mathrm{m}}(\underline{\mathbf{R}},t)$$

$$\nabla \times \underline{\mathbf{H}}(\underline{\mathbf{R}},t) = \frac{\partial}{\partial t}\underline{\mathbf{D}}(\underline{\mathbf{R}},t) + \underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t)$$

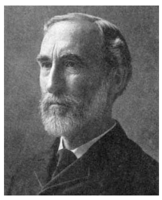
$$\nabla \bullet \underline{\mathbf{D}}(\underline{\mathbf{R}},t) = \rho_{\mathrm{e}}(\underline{\mathbf{R}},t)$$

$$\nabla \bullet \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \rho_{\mathrm{m}}(\underline{\mathbf{R}},t)$$

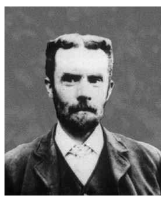
$$\nabla \bullet \underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t) = -\frac{\partial}{\partial t}\rho_{\mathrm{e}}(\underline{\mathbf{R}},t)$$

$$\nabla \bullet \underline{\mathbf{J}}_{\mathrm{m}}(\underline{\mathbf{R}},t) = -\frac{\partial}{\partial t}\rho_{\mathrm{m}}(\underline{\mathbf{R}},t)$$

Josiah Willard Gibbs (1839-1903)

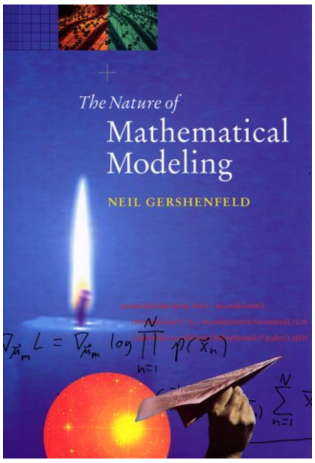


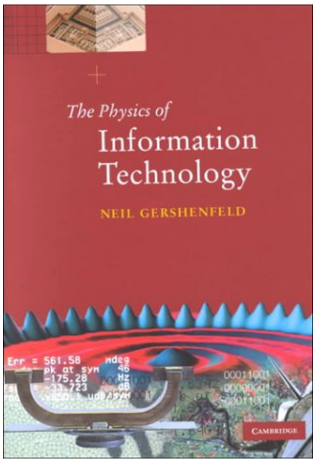
Oliver Heaviside (1850-1925)

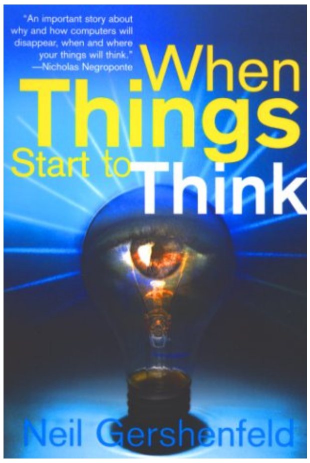


Paul Adrien Maurice Dirac (1902-1984)

… Other Books / … andere Bücher







End of Lecture 2 /
Ende der 2. Vorlesung