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

5th Lecture / 5. Vorlesung

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Electrostatic (ES) Fields / Elektrostatische (ES) Felder

Electrostatic Potential / Elektrostatisches Potential

Integral Form / Integralform

$$\oint_{C=\partial S} \underline{\mathbf{E}}(\underline{\mathbf{R}}) \cdot \mathbf{dR} = 0$$

$$\oiint_{S=\partial V} \underline{\mathbf{D}}(\underline{\mathbf{R}}) \cdot \mathbf{dS} = \iiint \rho_e(\underline{\mathbf{R}}) \mathrm{d}V$$

Differential Form / Differentialform

$$\nabla \times \underline{\mathbf{E}}(\underline{\mathbf{R}}) = \underline{\mathbf{0}}$$

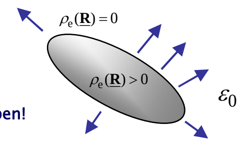
$$\nabla \cdot \underline{\mathbf{D}}(\underline{\mathbf{R}}) = \rho_e(\underline{\mathbf{R}})$$

Unknown! / Unbekannt! $\underline{\mathbf{E}}(\underline{\mathbf{R}}), \underline{\mathbf{D}}(\underline{\mathbf{R}}) = ?$

Given, Prescribed! / Gegeben, vorgeschrieben!

Vacuum / Vakuum

$$\underline{\mathbf{D}}(\underline{\mathbf{R}}) = \varepsilon_0 \, \underline{\mathbf{E}}(\underline{\mathbf{R}})$$



$$\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = 0, \quad \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = 0, \quad \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = 0$$

$$\frac{\partial D_x}{\partial x} + \frac{\partial D_y}{\partial y} + \frac{\partial D_z}{\partial z} = \rho_e$$

Standard Way: Method of Potentials /
Standard Weg: Methode der Potentiale

Electrostatics / Elektrostatik: $\Phi_e(\underline{\mathbf{R}})$ [V] Scalar Electrostatic Potential / Skalares elektrostatisches Potential

Del (Nabla), Grad, Div, and Curl Operator in Cartesian Coordinate System / Nabla-, Grad-, Div- und Rot-Operator im Kartesischen Koordinatensystem

Del (Nabla) Operator / Nabla-Operator

$$\nabla = \underline{\mathbf{e}}_x \frac{\partial}{\partial x} + \underline{\mathbf{e}}_y \frac{\partial}{\partial y} + \underline{\mathbf{e}}_z \frac{\partial}{\partial z}$$

Gradient / Gradient

$$\text{grad} = \nabla = \underline{\mathbf{e}}_x \frac{\partial}{\partial x} + \underline{\mathbf{e}}_y \frac{\partial}{\partial y} + \underline{\mathbf{e}}_z \frac{\partial}{\partial z}$$

Divergence / Divergenz

$$\text{div} = \nabla \bullet = \left(\underline{\mathbf{e}}_x \frac{\partial}{\partial x} + \underline{\mathbf{e}}_y \frac{\partial}{\partial y} + \underline{\mathbf{e}}_z \frac{\partial}{\partial z} \right) \bullet$$

Curl / Rotation

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

Del (Nabla) Operator in Orthogonal Curvilinear Coordinate System / Nabla-Operator im orthogonal krummlinigen Koordinatensystem

Del (Nabla) Operator / Nabla-Operator

$$\nabla = \underline{\mathbf{e}}_{\xi_1} \frac{1}{h_{\xi_1}} \frac{\partial}{\partial \xi_1} + \underline{\mathbf{e}}_{\xi_2} \frac{1}{h_{\xi_2}} \frac{\partial}{\partial \xi_2} + \underline{\mathbf{e}}_{\xi_3} \frac{1}{h_{\xi_3}} \frac{\partial}{\partial \xi_3}$$

$$= \sum_{i=1}^{3} \underline{\mathbf{e}}_{\xi_i} \frac{1}{h_{\xi_i}} \frac{\partial}{\partial \xi_i}$$

$$= \underline{\mathbf{e}}_{\xi_i} \frac{1}{h_{\xi_i}} \frac{\partial}{\partial \xi_i}$$

Generalized Curvilinear Coordinates / Verallgemeinerte krummlinige Koordinaten

$$\xi_1, \xi_2, \xi_3 \quad \text{or} \quad \xi_i, i = 1,2,3$$

The del Operator / Der Nabla-Operator ∇ is a Vector / ist ein Vektor

Vector-analytical Expressions in the Different Coordinate Systems / Vektoranalytische Ausdrücke in den verschiedenen Koordinatensystemen

	Cartesian Coordinates / Kartesische Koordinaten	Cylindrical Coordinates / Zylinderkoordinaten	Spherical Coordinates / Kugelkoordinaten
$\underline{\mathbf{dR}}$	$\mathrm{d}x\underline{\mathbf{e}}_x + \mathrm{d}y\underline{\mathbf{e}}_y + \mathrm{d}z\underline{\mathbf{e}}_z$	$\mathrm{d}r\underline{\mathbf{e}}_r + r\mathrm{d}\varphi\underline{\mathbf{e}}_\varphi + \mathrm{d}z\underline{\mathbf{e}}_z$	$\mathrm{d}R\underline{\mathbf{e}}_R + R\mathrm{d}\vartheta\underline{\mathbf{e}}_\vartheta + R\sin\vartheta\,\mathrm{d}\varphi\underline{\mathbf{e}}_\varphi$
$\mathrm{grad}\,\Phi$ $= \nabla\Phi$	$\frac{\partial\Phi}{\partial x}\underline{\mathbf{e}}_x + \frac{\partial\Phi}{\partial y}\underline{\mathbf{e}}_y + \frac{\partial\Phi}{\partial z}\underline{\mathbf{e}}_z$	$\frac{\partial\Phi}{\partial r}\underline{\mathbf{e}}_r + \frac{1}{r}\frac{\partial\Phi}{\partial\varphi}\underline{\mathbf{e}}_\varphi + \frac{\partial\Phi}{\partial z}\underline{\mathbf{e}}_z$	$\frac{\partial\Phi}{\partial R}\underline{\mathbf{e}}_R + \frac{1}{R}\frac{\partial\Phi}{\partial\vartheta}\underline{\mathbf{e}}_\vartheta + \frac{1}{R\sin\vartheta}\frac{\partial\Phi}{\partial\varphi}\underline{\mathbf{e}}_\varphi$
$\mathrm{div}\,\underline{\mathbf{A}}$ $= \nabla\bullet\underline{\mathbf{A}}$	$\frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$	$\frac{1}{r}\frac{\partial(rA_r)}{\partial r} + \frac{1}{r}\frac{\partial A_\varphi}{\partial\varphi} + \frac{\partial A_z}{\partial z}$	$\frac{1}{R^2}\frac{\partial(R^2A_R)}{\partial R} + \frac{1}{R\sin\vartheta}\frac{\partial(\sin\vartheta A_\vartheta)}{\partial\vartheta} + \frac{1}{R\sin\vartheta}\frac{\partial A_\varphi}{\partial\varphi}$
$\mathrm{curl}\,\underline{\mathbf{A}}$ $= \mathrm{rot}\,\underline{\mathbf{A}}$ $= \nabla\times\underline{\mathbf{A}}$	$\left[\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}\right]\underline{\mathbf{e}}_x$ $+\left[\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}\right]\underline{\mathbf{e}}_y$ $+\left[\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}\right]\underline{\mathbf{e}}_z$	$\left[\frac{1}{r}\frac{\partial A_z}{\partial\varphi} - \frac{\partial A_\varphi}{\partial z}\right]\underline{\mathbf{e}}_r$ $+\left[\frac{\partial A_r}{\partial z} - \frac{\partial A_z}{\partial r}\right]\underline{\mathbf{e}}_\varphi$ $+\frac{1}{r}\left[\frac{\partial(rA_\varphi)}{\partial r} - \frac{\partial A_r}{\partial\varphi}\right]\underline{\mathbf{e}}_z$	$\frac{1}{R\sin\vartheta}\left[\frac{\partial(\sin\vartheta A_\varphi)}{\partial\vartheta} - \frac{\partial A_\vartheta}{\partial\varphi}\right]\underline{\mathbf{e}}_R$ $+\frac{1}{R}\left[\frac{1}{\sin\vartheta}\frac{\partial A_R}{\partial\varphi} - \frac{\partial(RA_\varphi)}{\partial R}\right]\underline{\mathbf{e}}_\vartheta$ $+\frac{1}{R}\left[\frac{\partial(RA_\vartheta)}{\partial R} - \frac{\partial A_R}{\partial\vartheta}\right]\underline{\mathbf{e}}_\varphi$

Vector-Analytical Expressions in the Different Coordinate Systems / Vektoranalytische Ausdrücke in den verschiedenen Koordinatensystemen

	Cartesian Coordinates / Kartesische Koordinaten	Cylindrical Coordinates / Zylinderkoordinaten	Spherical Coordinates / Kugelkoordinaten
$\mathrm{div}\,\mathrm{grad}\,\Phi$ $= \nabla\bullet\nabla\Phi$ $= \nabla^2\Phi$ $= \Delta\Phi$	$\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2} + \frac{\partial^2\Phi}{\partial z^2}$	$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Phi}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2\Phi}{\partial\varphi^2} + \frac{\partial^2\Phi}{\partial z^2}$	$\frac{1}{R^2}\frac{\partial}{\partial R}\left(R^2\frac{\partial\Phi}{\partial R}\right) + \frac{1}{R^2\sin\vartheta}\frac{\partial}{\partial\vartheta}\left(\sin\vartheta\frac{\partial\Phi}{\partial\vartheta}\right)$ $+\frac{1}{R^2\sin^2\vartheta}\left(\frac{\partial^2\Phi}{\partial\varphi^2}\right)$
$\mathrm{div}\,\mathrm{grad}\underline{\mathbf{A}}$ $= \nabla\bullet\nabla\underline{\mathbf{A}}$ $= \nabla^2\underline{\mathbf{A}}$ $= \Delta\underline{\mathbf{A}}$	$\Delta A_x\underline{\mathbf{e}}_x$ $+\Delta A_y\underline{\mathbf{e}}_y$ $+\Delta A_z\underline{\mathbf{e}}_z$	$\left[\Delta A_r - \frac{1}{r^2}A_r - \frac{2}{r^2}\frac{\partial A_\varphi}{\partial\varphi}\right]\underline{\mathbf{e}}_r$ $+\left[\Delta A_\varphi - \frac{1}{r^2}A_\varphi + \frac{2}{r^2}\frac{\partial A_r}{\partial\varphi}\right]\underline{\mathbf{e}}_\varphi$ $+\Delta A_z\underline{\mathbf{e}}_z$	$\left[\Delta A_R - \frac{2}{R^2}A_R - \frac{2\cot\vartheta}{R^2}A_\vartheta - \frac{2}{R^2}\frac{\partial A_\vartheta}{\partial\vartheta} - \frac{2}{R^2\sin\vartheta}\frac{\partial A_\varphi}{\partial\varphi}\right]\underline{\mathbf{e}}_R$ $+\left[\Delta A_\vartheta + \frac{2}{R^2}\frac{\partial A_R}{\partial\vartheta} - \frac{1}{R^2\sin^2\vartheta}A_\vartheta - \frac{2\cos\vartheta}{R^2\sin^2\vartheta}\frac{\partial A_\varphi}{\partial\varphi}\right]\underline{\mathbf{e}}_\vartheta$ $+\left[\Delta A_\varphi + \frac{2}{R^2\sin\vartheta}\frac{\partial A_R}{\partial\varphi} - \frac{1}{R^2\sin^2\vartheta}A_\varphi + \frac{2\cos\vartheta}{R^2\sin^2\vartheta}\frac{\partial A_\vartheta}{\partial\varphi}\right]\underline{\mathbf{e}}_\varphi$

Electrostatic (ES) Fields / Elektrostatische (ES) Felder
Electrostatic Potential / Elektrostatisches Potential

Integral Form / Integralform

$$\oint_{C=\partial S} \underline{\mathbf{E}}(\underline{\mathbf{R}}) \bullet \underline{\mathbf{dR}} = 0$$

Differential Form / Differentialform

$$\nabla \times \underline{\mathbf{E}}(\underline{\mathbf{R}}) = \underline{\mathbf{0}}$$

Irrotational Field can be always Represented by a Gradient Field / Rotationsfreies Feld kann immer als Gradientenfeld dargestellt werden

$$\underline{\mathbf{E}}(\underline{\mathbf{R}}) = -\nabla \Phi_e(\underline{\mathbf{R}})$$

Electrostatic Potential / Elektrostatisches Potential

$$\Phi_e(\underline{\mathbf{R}}) \; [\mathrm{V}]$$

because / weil

$$\begin{aligned} \nabla \times \underline{\mathbf{E}}(\underline{\mathbf{R}}) &= \nabla \times \left[-\nabla \Phi_e(\underline{\mathbf{R}}) \right] \\ &= -\nabla \times \nabla \Phi_e(\underline{\mathbf{R}}) \\ &= \underline{\mathbf{0}} \end{aligned}$$

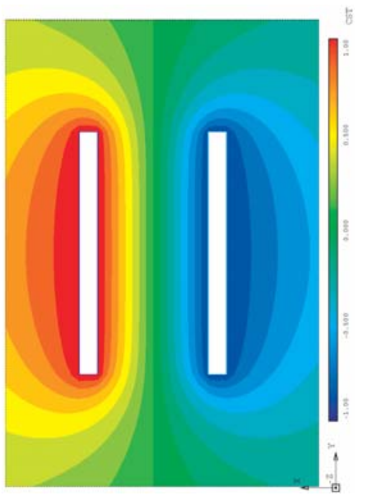
In General / Im allgemeinen

$$\nabla \times \nabla \equiv \underline{\mathbf{0}}$$

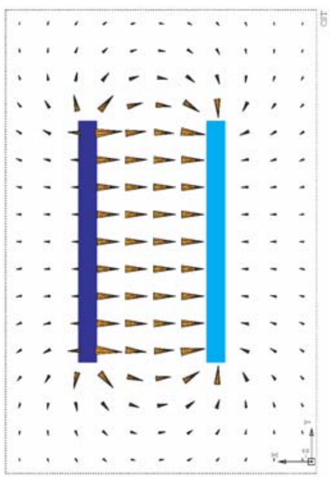
General Vector Analytic Property / Allgemeine Vektoridentität

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

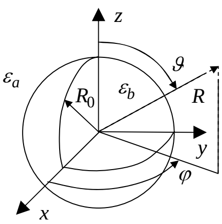
Scalar Field: Electrostatic Potential / Skalarfeld: Elektrostatisches Potenzial



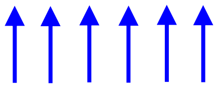
Vector Field: Electrostatic Field Strength / Vektorfeld: Elektrostatische Feldstärke



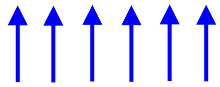
Example: Dielectric Sphere in a Homogeneous Electrostatic Field / Beispiel: Dielektrische Kugel im homogenen elektrostatischen Feld (1)



$\underline{\mathbf{E}}_0 = E_0 \underline{\mathbf{e}}_z$



$\underline{\mathbf{E}}_0 = E_0 \underline{\mathbf{e}}_z$



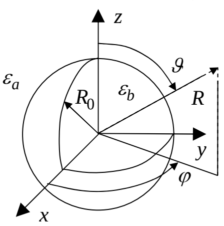
$\varepsilon(\underline{\mathbf{R}}) = \varepsilon_a$

$$\varepsilon(\underline{\mathbf{R}}) = \begin{cases} \varepsilon_b & 0 < R \le R_0 \\ \varepsilon_a & R > R_0 \end{cases}$$

$\underline{\mathbf{E}}(\underline{\mathbf{R}}) = E_0 \hat{\underline{\mathbf{E}}}_0$

$\underline{\mathbf{E}}(\underline{\mathbf{R}}) = E_0 \underline{\mathbf{e}}_z + \underline{\mathbf{E}}_b(\underline{\mathbf{R}})$

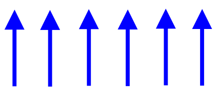
Example: Dielectric Sphere in a Homogeneous Electrostatic Field / Beispiel: Dielektrische Kugel im homogenen elektrostatischen Feld (2)



$$\varepsilon(\underline{\mathbf{R}}) = \begin{cases} \varepsilon_b & 0 < R \le R_0 \\ \varepsilon_a & R > R_0 \end{cases}$$

$\underline{\mathbf{E}}(\underline{\mathbf{R}}) = E_0 \underline{\mathbf{e}}_z + \underline{\mathbf{E}}_b(\underline{\mathbf{R}})$

$\underline{\mathbf{E}}_0 = E_0 \underline{\mathbf{e}}_z$



$$\Phi_e(\underline{\mathbf{R}}) = \begin{cases} -E_0 \beta R \cos\vartheta & 0 < R \le R_0 \\ -E_0 \left[1 - \dfrac{\alpha}{R^3}\right] R \cos\vartheta & R > R_0 \end{cases}$$

$$\alpha = \frac{\varepsilon_b - \varepsilon_a}{\varepsilon_b + 2\varepsilon_a} R_0^3$$

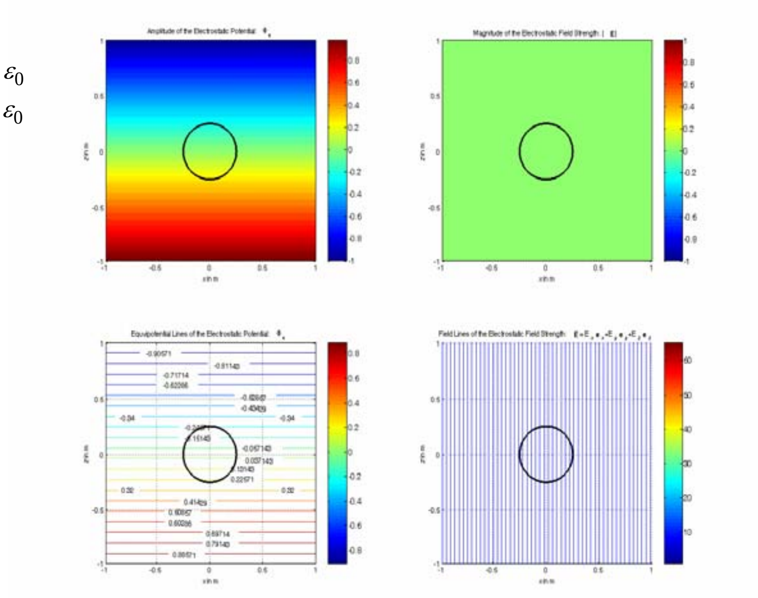
$$\underline{\mathbf{E}}(\underline{\mathbf{R}}) = \begin{cases} E_0 \beta \left[\cos\vartheta\, \underline{\mathbf{e}}_R - \cos\vartheta\, \underline{\mathbf{e}}_\vartheta\right] & 0 < R \le R_0 \\ E_0 \left[\left(1 - \dfrac{2\alpha}{R^3}\right) \cos\vartheta\, \underline{\mathbf{e}}_R - \left(1 - \dfrac{\alpha}{R^3}\right) \sin\vartheta\, \underline{\mathbf{e}}_\vartheta\right] & R > R_0 \end{cases}$$

$$\beta = \frac{3\varepsilon_a}{\varepsilon_b + 2\varepsilon_a}$$

Example: Dielectric Sphere in a Homogeneous Electrostatic Field / Beispiel: Dielektrische Kugel im homogenen elektrostatischen Feld (3)

$\varepsilon_a = \varepsilon_0$

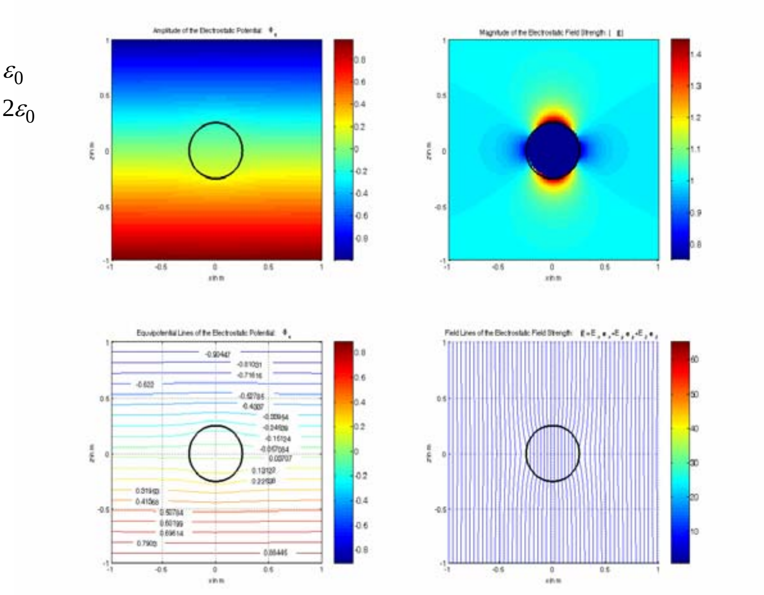
$\varepsilon_b = \varepsilon_0$



Example: Dielectric Sphere in a Homogeneous Electrostatic Field / Beispiel: Dielektrische Kugel im homogenen elektrostatischen Feld (4)

$\varepsilon_a = \varepsilon_0$

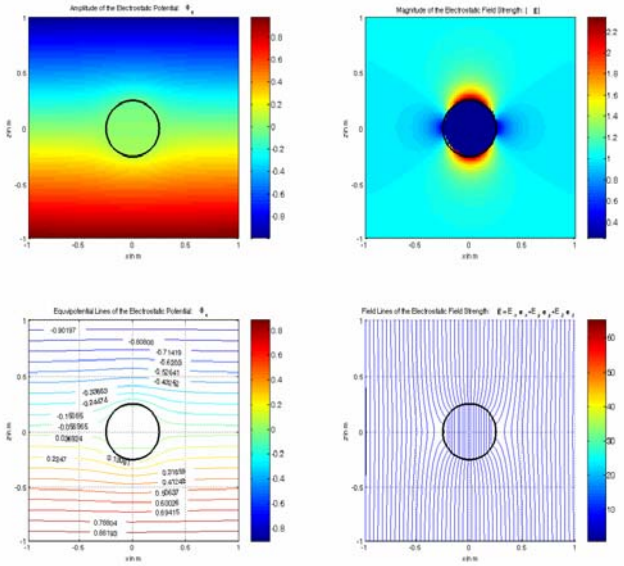
$\varepsilon_b = 2\varepsilon_0$



Example: Dielectric Sphere in a Homogeneous Electrostatic Field / Beispiel: Dielektrische Kugel im homogenen elektrostatischen Feld (5)

$\varepsilon_a = \varepsilon_0$

$\varepsilon_b = 10\varepsilon_0$



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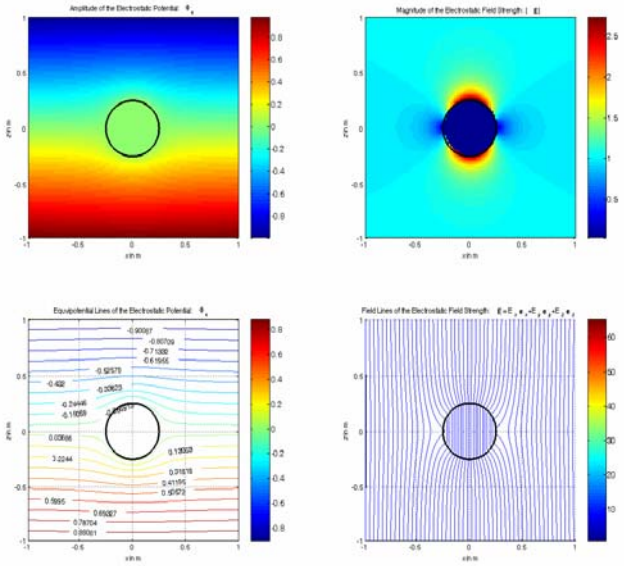
Example: Dielectric Sphere in a Homogeneous Electrostatic Field / Beispiel: Dielektrische Kugel im homogenen elektrostatischen Feld (6/1)

$\varepsilon_a = \varepsilon_0$

$\varepsilon_b = 100\varepsilon_0$



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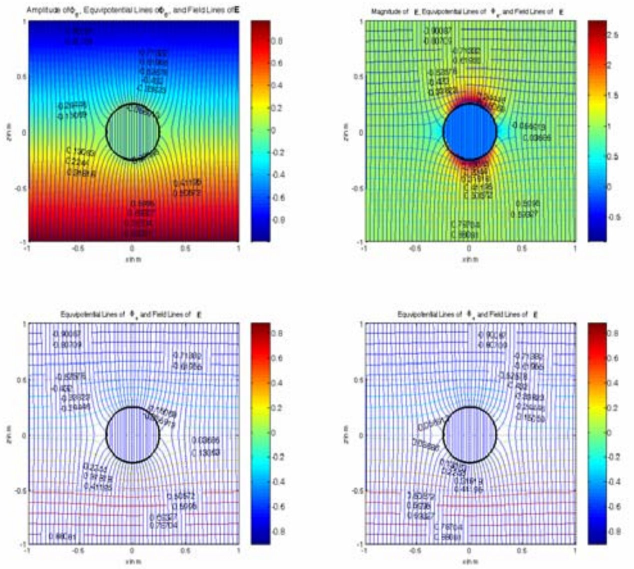
Example: Dielectric Sphere in a Homogeneous Electrostatic Field / Beispiel: Dielektrische Kugel im homogenen elektrostatischen Feld (6/2)

$\varepsilon_a = \varepsilon_0$

$\varepsilon_b = 100\varepsilon_0$



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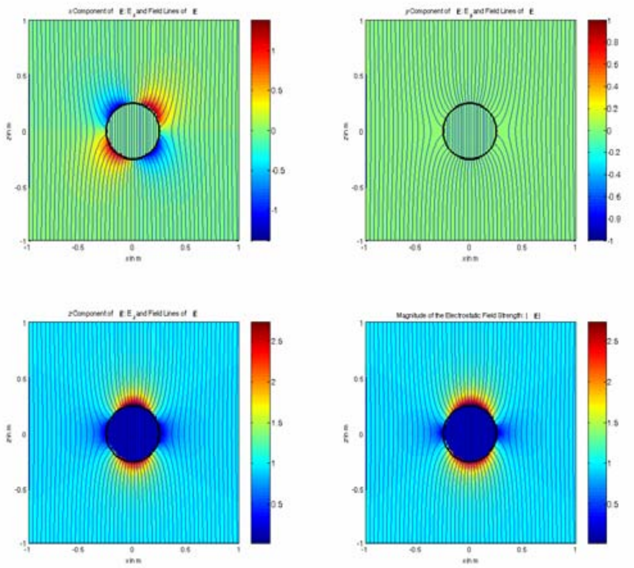
Example: Dielectric Sphere in a Homogeneous Electrostatic Field / Beispiel: Dielektrische Kugel im homogenen elektrostatischen Feld (6/3)

$\varepsilon_a = \varepsilon_0$

$\varepsilon_b = 100\varepsilon_0$



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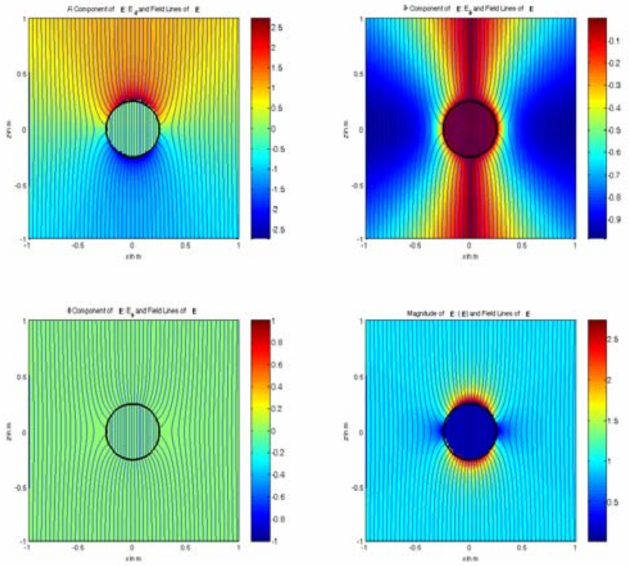
Example: Dielectric Sphere in a Homogeneous Electrostatic Field / Beispiel: Dielektrische Kugel im homogenen elektrostatischen Feld (6/4)

$\varepsilon_a = \varepsilon_0$

$\varepsilon_b = 100\varepsilon_0$



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Electrostatic (ES) Fields – Poisson and Laplace Equation / Elektrostatische (ES) Felder – Poisson- und Laplace-Gleichung (1)

Differential Form / Differentialform

$$\nabla \times \underline{\mathbf{E}}(\underline{\mathbf{R}}) = \underline{\mathbf{0}}$$

$$\underline{\mathbf{E}}(\underline{\mathbf{R}}) = -\nabla \Phi_e(\underline{\mathbf{R}})$$

$$\nabla \bullet \underline{\mathbf{D}}(\underline{\mathbf{R}}) = \rho_e(\underline{\mathbf{R}})$$

Vacuum / Vakuum

$$\underline{\mathbf{D}}(\underline{\mathbf{R}}) = \varepsilon_0 \, \underline{\mathbf{E}}(\underline{\mathbf{R}}) = -\varepsilon_0 \nabla \Phi_e(\underline{\mathbf{R}})$$

because / weil

$$\nabla \bullet \underline{\mathbf{D}}(\underline{\mathbf{R}}) = \varepsilon_0 \nabla \bullet \underline{\mathbf{E}}(\underline{\mathbf{R}}) = -\varepsilon_0 \nabla \bullet \nabla \Phi_e(\underline{\mathbf{R}}) = \rho_e(\underline{\mathbf{R}})$$

or / oder

$$\underbrace{\nabla \bullet \nabla}_{\nabla^2 = \Delta} \Phi_e(\underline{\mathbf{R}}) = \begin{cases} -\dfrac{\rho_e(\underline{\mathbf{R}})}{\varepsilon_0} & \text{for / für } \rho_e(\underline{\mathbf{R}}) \neq 0 \quad \text{Poisson Equation / Poisson-Gleichung} \\ 0 & \text{for / für } \rho_e(\underline{\mathbf{R}}) = 0 \quad \text{Laplace Equation / Laplace-Gleichung} \end{cases}$$

Laplace Operator / Laplace-Operator

$$\nabla \bullet \nabla = \nabla^2 = \Delta$$

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Electrostatic (ES) Fields – Poisson and Laplace Equation / Elektrostatische (ES) Felder – Poisson- und Laplace-Gleichung (2)

$$\underbrace{\nabla\bullet\nabla}_{\nabla^2=\Delta}\Phi_e(\mathbf{R}) = \begin{cases} -\dfrac{\rho_e(\mathbf{R})}{\varepsilon_0} & \text{for / für } \rho_e(\mathbf{R}) \neq 0 \quad \text{Poisson Equation / Poisson-Gleichung} \\ 0 & \text{for / für } \rho_e(\mathbf{R}) = 0 \quad \text{Laplace Equation / Laplace-Gleichung} \end{cases}$$

Laplace Operator / Laplace-Operator

$$\nabla\bullet\nabla = \nabla^2 = \Delta$$

Laplace Operator in Cartesian Coordinates / Laplace-Operator in Kartesischen Koordinaten

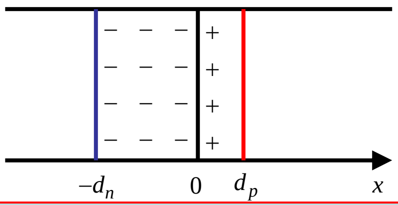
$$\begin{aligned} \nabla\bullet\nabla &= \left(\underline{\mathbf{e}}_x\frac{\partial}{\partial x}+\underline{\mathbf{e}}_y\frac{\partial}{\partial y}+\underline{\mathbf{e}}_z\frac{\partial}{\partial z}\right)\bullet\left(\underline{\mathbf{e}}_x\frac{\partial}{\partial x}+\underline{\mathbf{e}}_y\frac{\partial}{\partial y}+\underline{\mathbf{e}}_z\frac{\partial}{\partial z}\right) \\ &= \underline{\mathbf{e}}_{x_i}\frac{\partial}{\partial x_i}\bullet\underline{\mathbf{e}}_{x_j}\frac{\partial}{\partial x_j} \\ &= \frac{\partial}{\partial x_i}\frac{\partial}{\partial x_j}\underbrace{\underline{\mathbf{e}}_{x_i}\bullet\underline{\mathbf{e}}_{x_j}}_{\delta_{ij}} \\ &= \frac{\partial}{\partial x_i}\frac{\partial}{\partial x_i} \\ &= \frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2} = \nabla^2 = \Delta \end{aligned}$$

Electrostatic (ES) Fields – Poisson and Laplace Equation / Elektrostatische (ES) Felder – Poisson- und Laplace-Gleichung (3)

Laplace Operator in Cartesian Coordinates / Laplace-Operator in Kartesischen Koordinaten

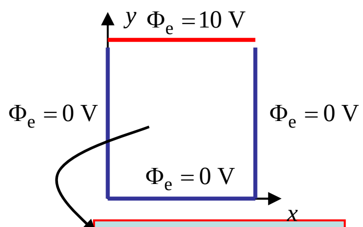
$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)\Phi_e(x,y,z) = \begin{cases} -\dfrac{\rho_e(x,y,z)}{\varepsilon_0} & \text{for / für } \rho_e(x,y,z) \neq 0 \quad \text{Poisson Equation / Poisson-Gleichung} \\ 0 & \text{for / für } \rho_e(x,y,z) = 0 \quad \text{Laplace Equation / Laplace-Gleichung} \end{cases}$$

Example: pn Junction – pn Diode / Beispiel: pn-Übergang – pn Diode



$$\frac{\mathrm{d}^2}{\mathrm{d}x^2}\Phi_e(x) = \frac{e}{\varepsilon}\begin{cases} -n_e & \text{for / für } -d_n \le x \le 0 \\ n_e & \text{for / für } 0 \le x \le d_p \end{cases}$$

Example: / Beispiel:



$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\Phi_e(x,y) = 0$$

➡ Separation of Variables / Separation der Variablen !

End of Lecture 5 /
Ende der 5. Vorlesung