Eletromagnetismo

$$\vec{\nabla} \cdot \vec{D} = \frac{\rho}{\epsilon_0}$$

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

$$\vec{\nabla} \cdot \vec{B} = 0$$

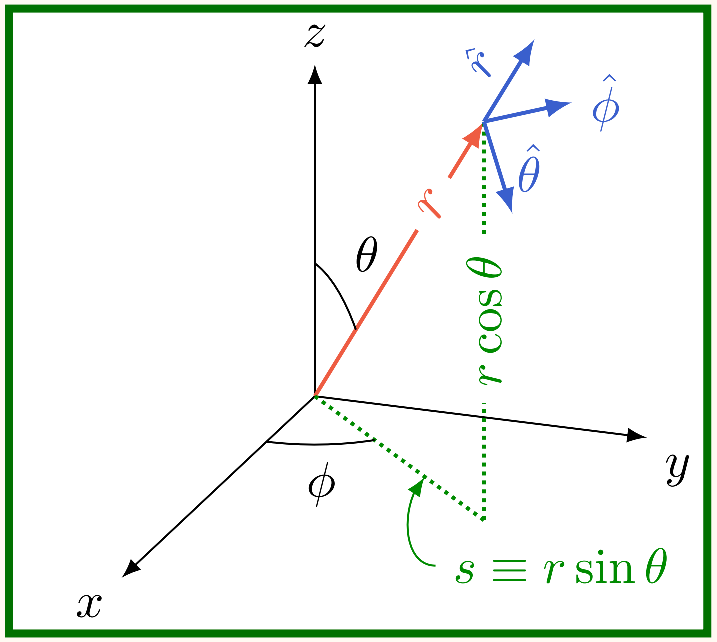
$$\vec{\nabla} \times \vec{H} = \vec{j} + \epsilon_0 \frac{\partial \vec{D}}{\partial t}$$

Aula de 14 de junho

Métodos especiais

Coordenadas esféricas

$$d\vec{\ell} = dr\,\hat{r} + r\,d\theta\,\hat{\theta} + r\sin\theta\,d\phi\,\hat{\phi}$$



$$\vec{\nabla} t = \frac{\partial t}{\partial r}\hat{r} + \frac{1}{r}\frac{\partial t}{\partial \theta}\hat{\theta} + \frac{1}{r\sin\theta}\frac{\partial t}{\partial \phi}\hat{\phi}$$

$$\vec{\nabla}\cdot\vec{v} = \frac{1}{r^2}\frac{\partial(r^2 v_r)}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial(\sin\theta\, v_\theta)}{\partial\theta} + \frac{1}{r\sin\theta}\frac{\partial v_\phi}{\partial\phi}$$

$$\vec{\nabla}\times\vec{v} = \frac{1}{r\sin\theta}\left[\frac{\partial}{\partial\theta}\left(\sin\theta\, v_\phi\right) - \frac{\partial v_\theta}{\partial\phi}\right]\hat{r}$$

$$+ \frac{1}{r}\left[\frac{1}{\sin\theta}\frac{\partial v_r}{\partial\phi} - \frac{\partial}{\partial r}\left(r v_\phi\right)\right]\hat{\theta} + \frac{1}{r}\left[\frac{\partial}{\partial r}\left(r\, v_\theta\right) - \frac{\partial v_r}{\partial\theta}\right]\hat{\phi}$$

$$\nabla^2 t = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial t}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\,\frac{\partial t}{\partial\theta}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial^2 t}{\partial\phi^2}$$

Coordenadas cilíndricas

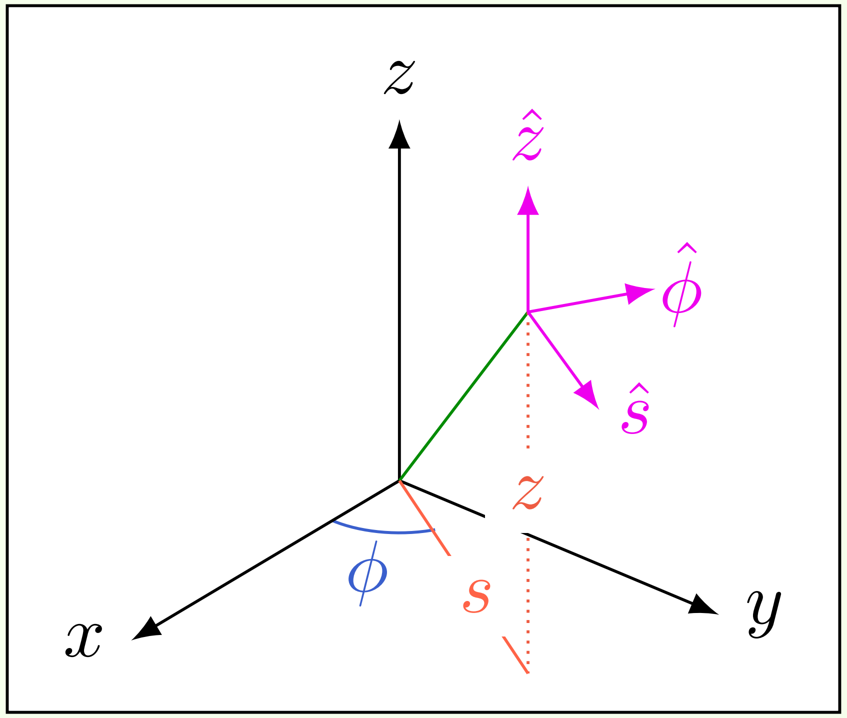
$$\mathrm{d}\vec{\ell} = \mathrm{d}s\,\hat{s} + s\,\mathrm{d}\phi\,\hat{\phi} + \mathrm{d}z\,\hat{z}$$

$$\vec{\nabla} T = \frac{\partial T}{\partial s}\hat{s} + \frac{1}{s}\frac{\partial T}{\partial \phi}\hat{\phi} + \frac{\partial T}{\partial z}\hat{z}$$

$$\vec{\nabla}\cdot\vec{v} = \frac{1}{s}\frac{\partial(s v_s)}{\partial s} + \frac{1}{s}\frac{\partial v_\phi}{\partial \phi} + \frac{\partial v_z}{\partial z}$$

$$\vec{\nabla}\times\vec{v} = \left(\frac{1}{s}\frac{\partial v_z}{\partial \phi} - \frac{\partial v_\phi}{\partial z}\right)\hat{s} + \left(\frac{\partial v_s}{\partial z} - \frac{\partial v_z}{\partial s}\right)\hat{\phi} + \frac{1}{s}\left(\frac{\partial(s v_\phi)}{\partial s} - \frac{\partial v_s}{\partial \phi}\right)\hat{z}$$

$$\nabla^2 T = \frac{1}{s}\frac{\partial}{\partial s}\left(s\frac{\partial T}{\partial s}\right) + \frac{1}{s^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2}$$

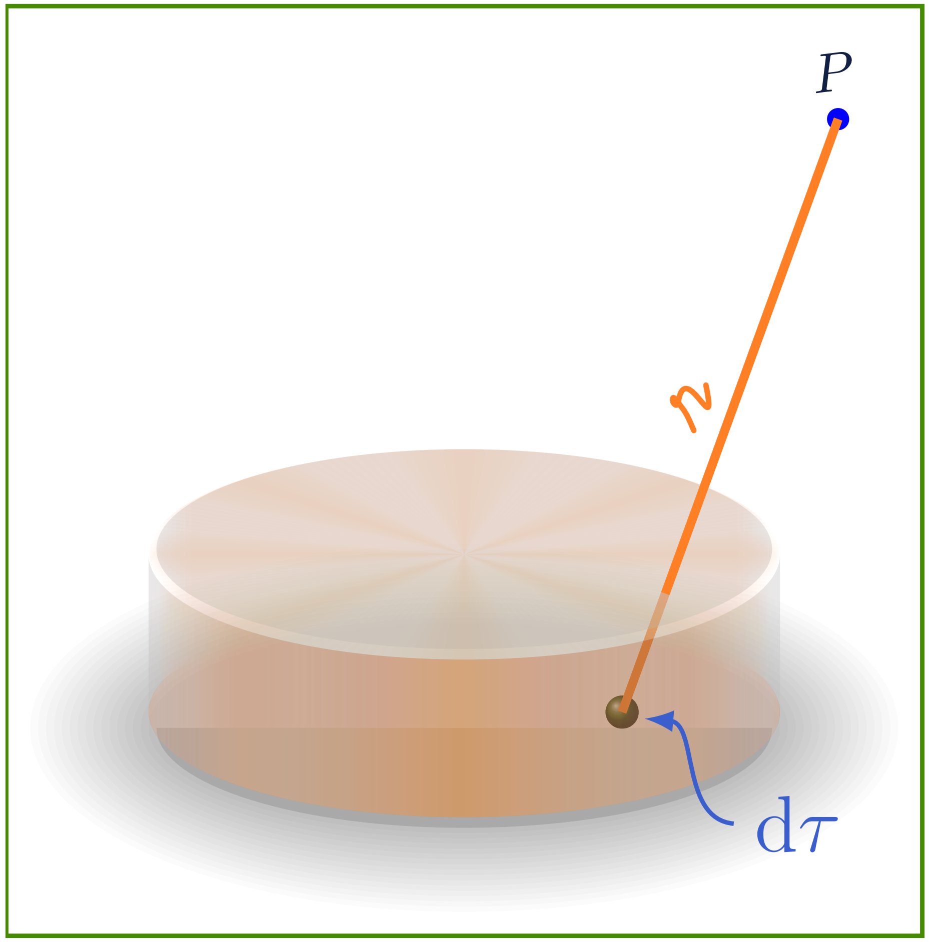


Expansão em multipolos

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\int \frac{\rho(\vec{r}\,')}{\mathscr{r}}\,\mathrm{d}\tau$$

$$\frac{1}{\mathscr{r}} = \frac{1}{r}\sum_{\ell=0}^{\infty}\left(\frac{r'}{r}\right)^{\ell} P_\ell(\cos\theta')$$

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\sum_{n=0}^{\infty}\frac{1}{r^{n+1}}\int (r')^n P_n(\cos\theta')\rho(\vec{r'})\,\mathrm{d}\tau'$$



Expansão em multipolos

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0} \int \frac{\rho(\vec{r}\,')}{\mathscr{r}} \, \mathrm{d}\tau$$

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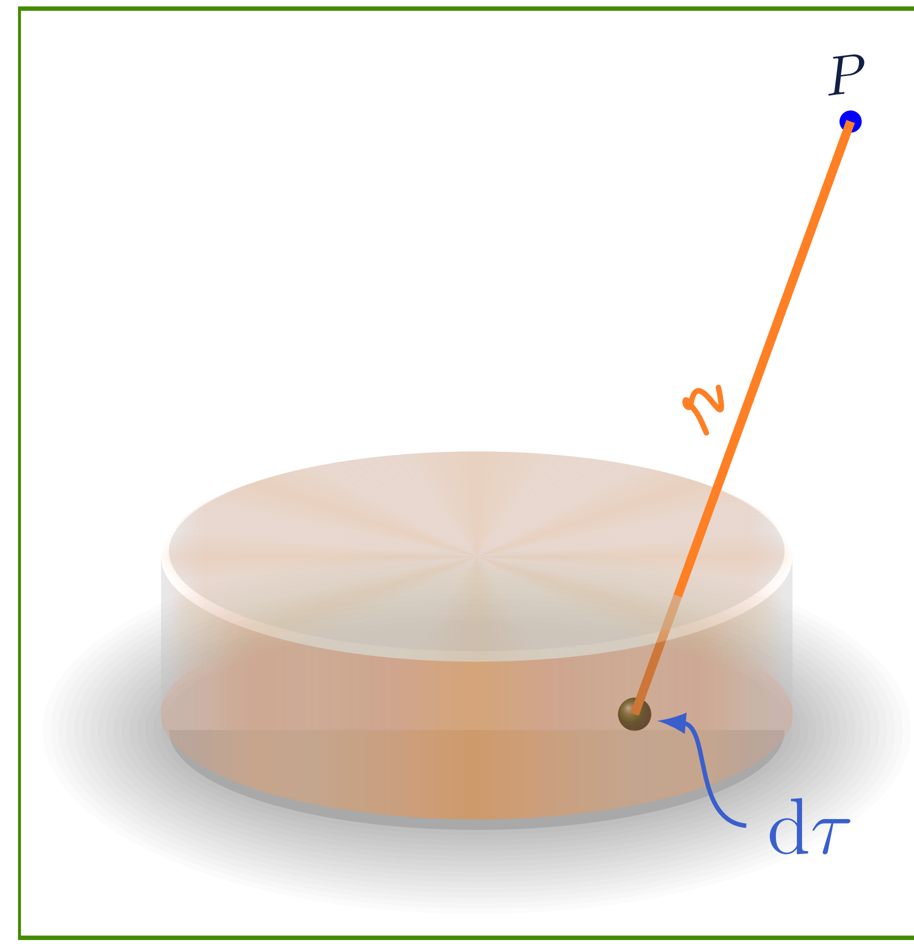

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0} \sum_{n=0}^{\infty} \frac{1}{r^{n+1}} \int (r')^n P_n(\cos\theta') \rho(\vec{r'}) \, \mathrm{d}\tau'$$

$$n = 0 \quad \Rightarrow \quad V(\vec{r}) = \frac{1}{4\pi\epsilon_0} \frac{Q}{r} \qquad \left[Q = \int \rho(\vec{r'}) \, \mathrm{d}\tau'\right]$$

$$n = 1 \quad \Rightarrow \quad V(\vec{r}) = \frac{1}{4\pi\epsilon_0} \frac{\vec{p} \cdot \hat{r}}{r^2} \qquad \left[\vec{p} = \int \vec{r'} \rho(\vec{r'}) \, \mathrm{d}\tau'\right]$$

Expansão em multipolos

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0} \int \frac{\rho(\vec{r}\,')}{\mathscr{r}} \, \mathrm{d}\tau$$

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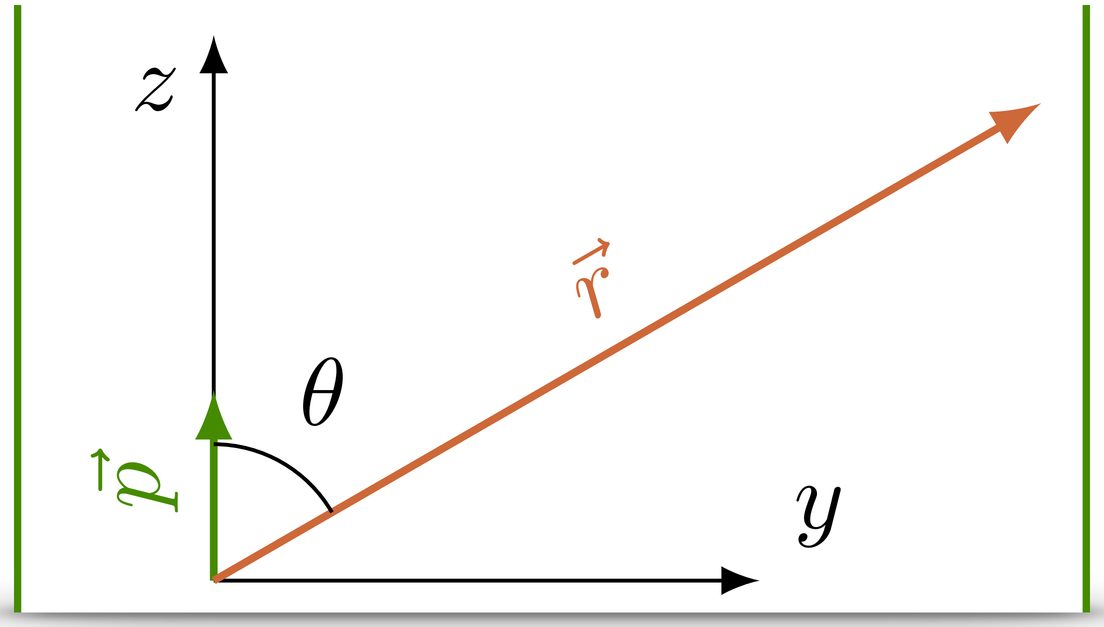

$$\vec{E} = -\vec{\nabla} V(r, \theta, \phi)$$

Expansão em multipolos

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\int \frac{\rho(\vec{r}\,')}{\mathscr{r}}\,\mathrm{d}\tau$$

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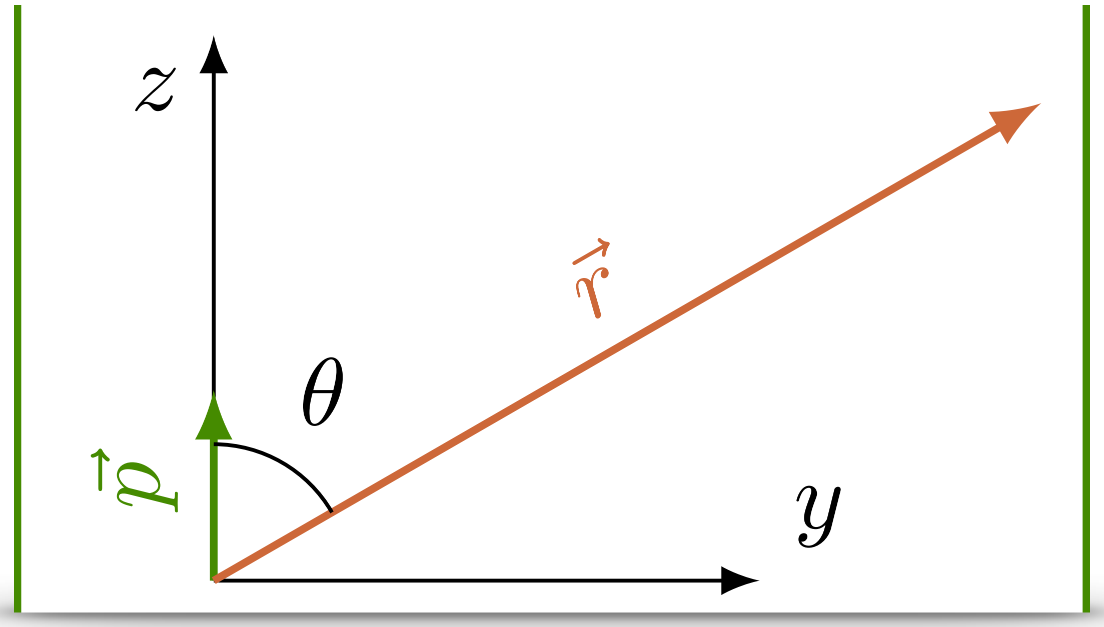

Expansão em multipolos

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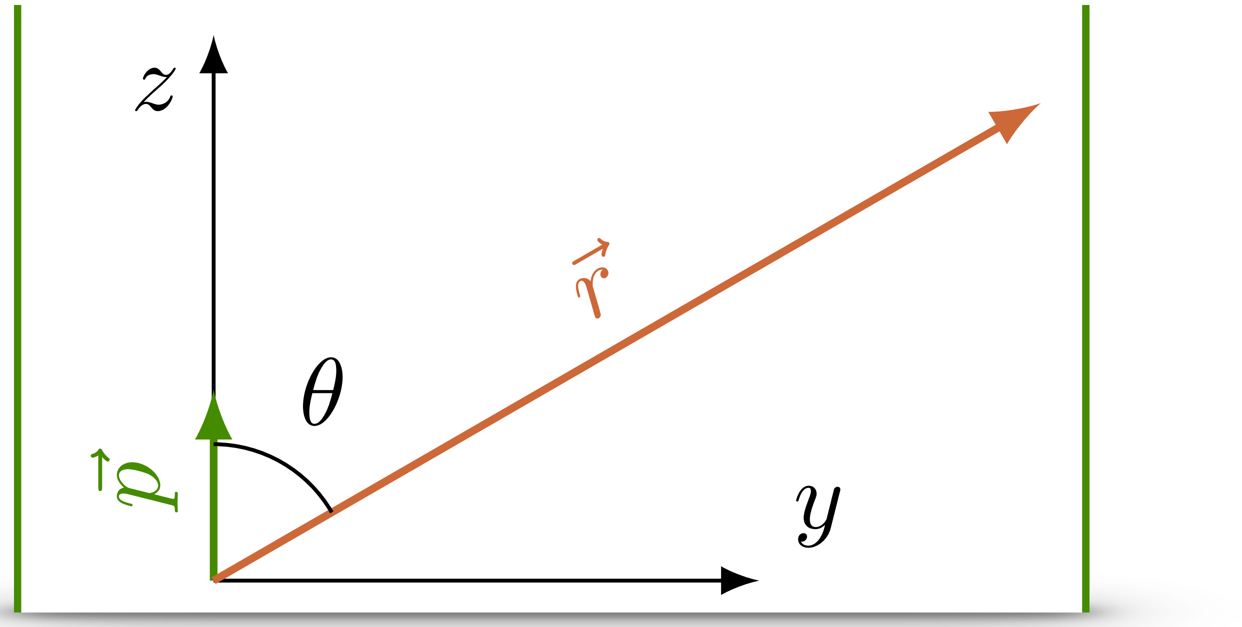

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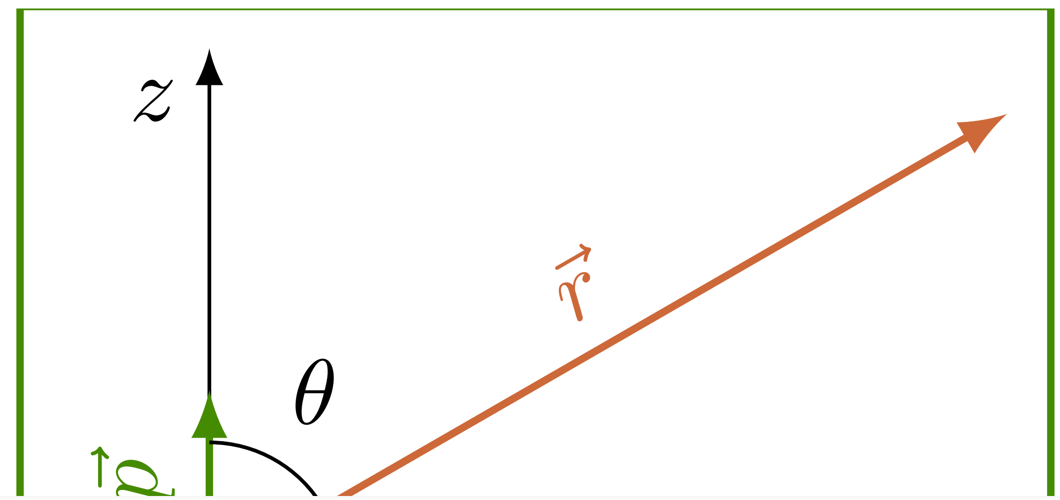

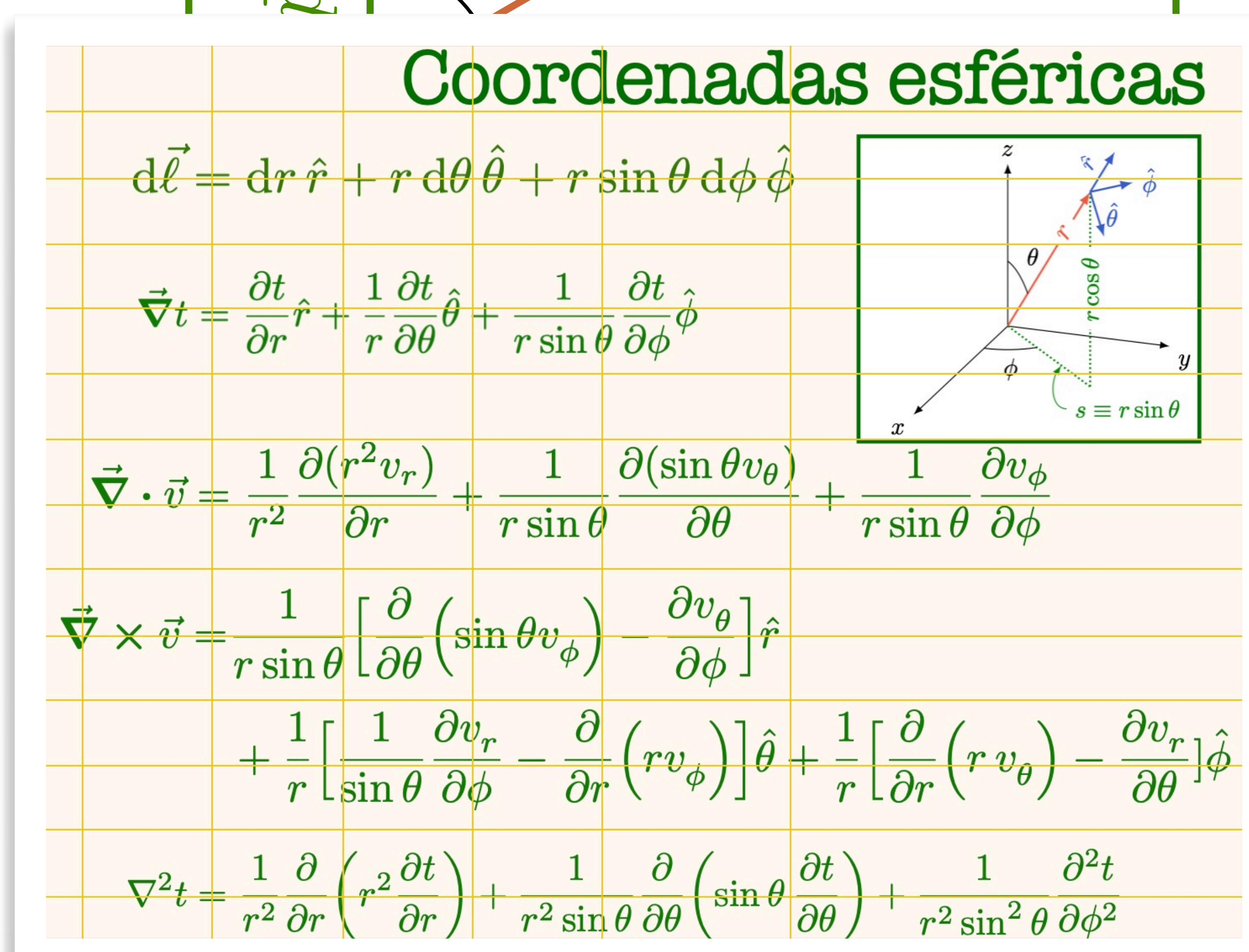

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$$\vec{\nabla} t = \frac{\partial t}{\partial r}\hat{r} + \frac{1}{r}\frac{\partial t}{\partial \theta}\hat{\theta} + \frac{1}{r\sin\theta}\frac{\partial t}{\partial \phi}\hat{\phi}$$

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$$\vec{\nabla}\times\vec{v} = \frac{1}{r\sin\theta}\left[\frac{\partial}{\partial\theta}\left(\sin\theta\, v_\phi\right) - \frac{\partial v_\theta}{\partial\phi}\right]\hat{r} + \frac{1}{r}\left[\frac{1}{\sin\theta}\frac{\partial v_r}{\partial\phi} - \frac{\partial}{\partial r}\left(r v_\phi\right)\right]\hat{\theta} + \frac{1}{r}\left[\frac{\partial}{\partial r}\left(r\, v_\theta\right) - \frac{\partial v_r}{\partial\theta}\right]\hat{\phi}$$

$$\nabla^2 t = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial t}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial t}{\partial\theta}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial^2 t}{\partial\phi^2}$$

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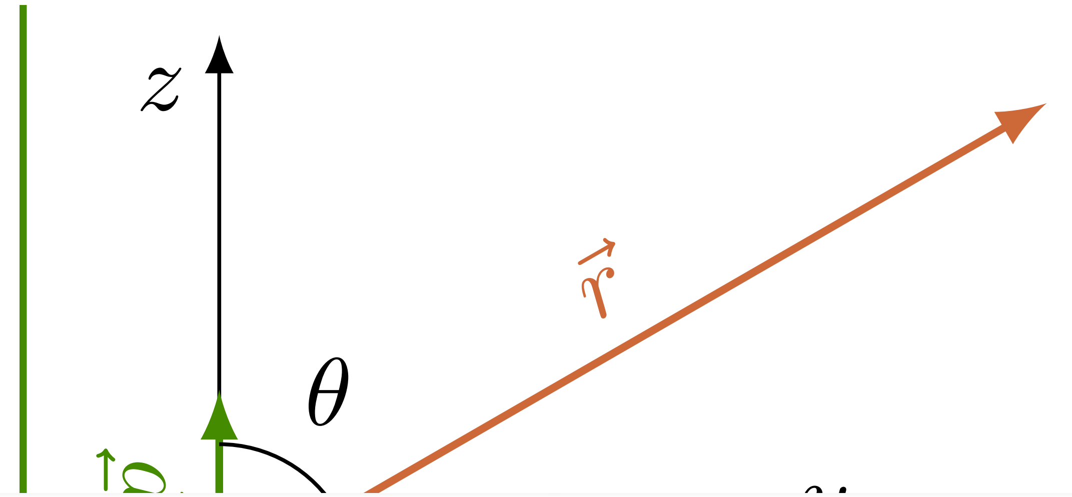

Coordenadas esféricas

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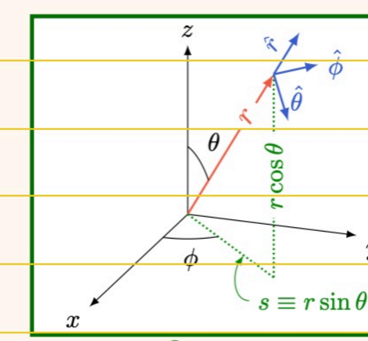

$$\vec{\nabla} t = \frac{\partial t}{\partial r}\hat{r} + \frac{1}{r}\frac{\partial t}{\partial \theta}\hat{\theta} + \frac{1}{r\sin\theta}\frac{\partial t}{\partial \phi}\hat{\phi}$$

$$\vec{\nabla}\cdot\vec{v} = \frac{1}{r^2}\frac{\partial(r^2 v_r)}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial(\sin\theta\, v_\theta)}{\partial\theta} + \frac{1}{r\sin\theta}\frac{\partial v_\phi}{\partial\phi}$$

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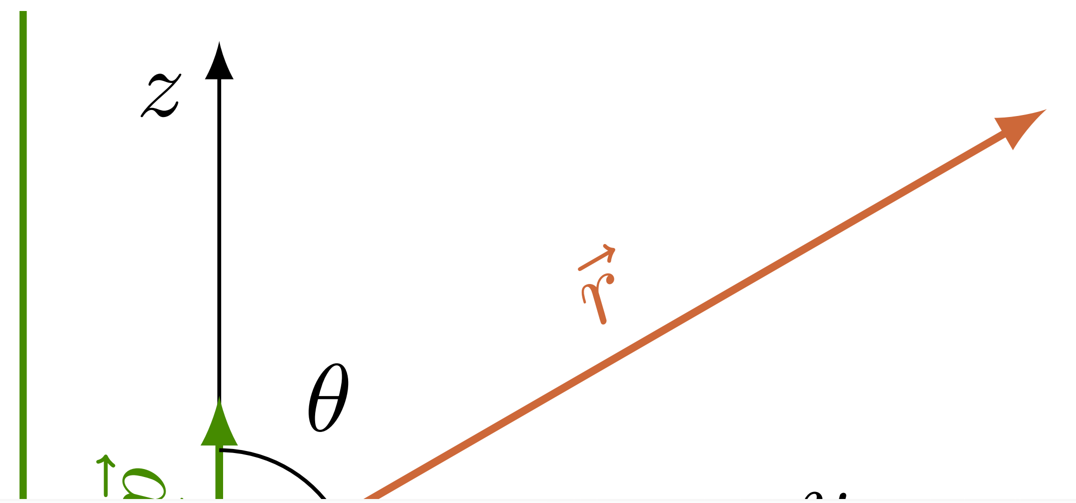
$$\vec{E} = \frac{1}{4\pi\epsilon_0} \frac{p}{r^3} (2\cos\theta\hat{r} + \sin\theta\hat{\theta})$$



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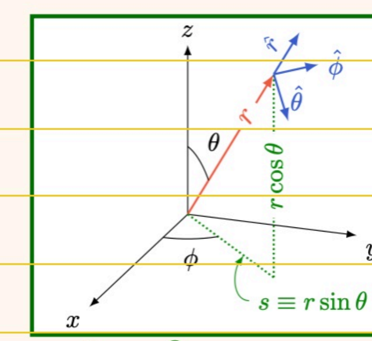

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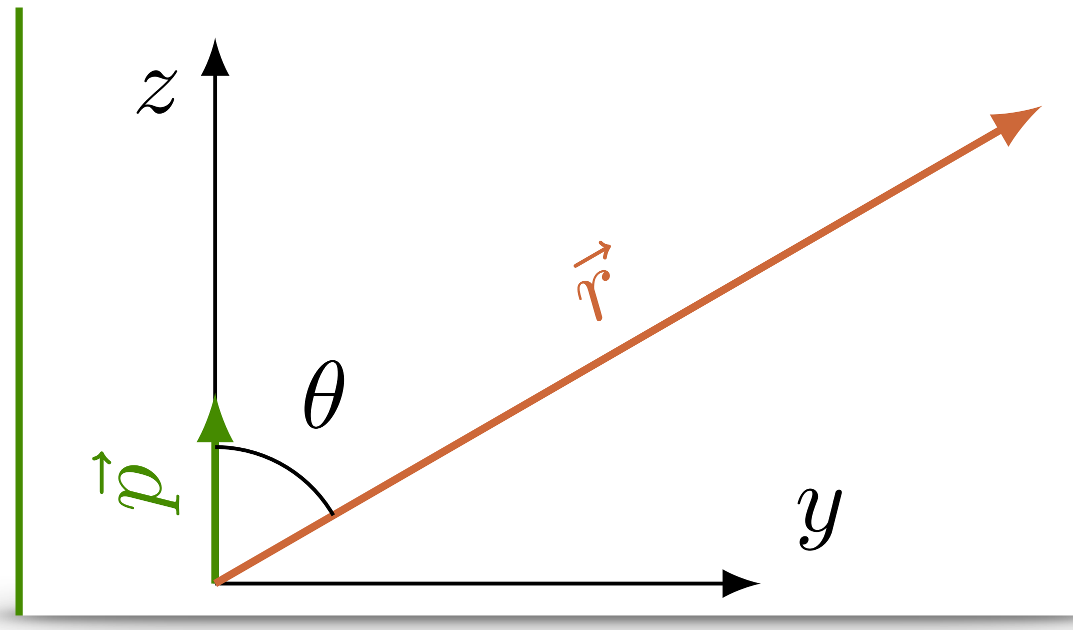

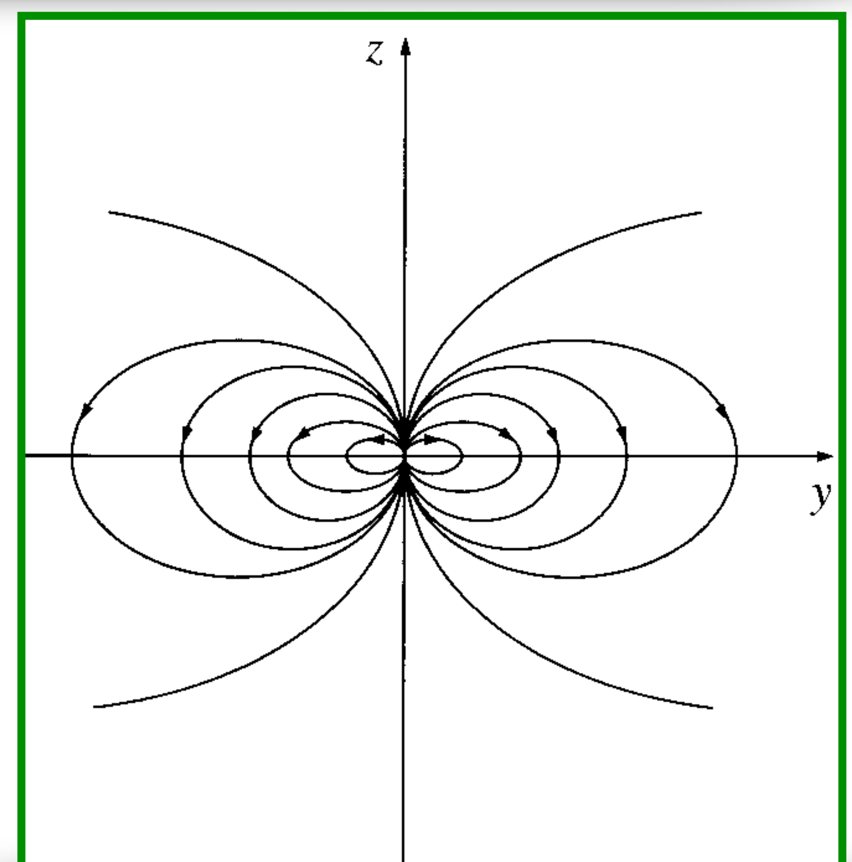

Eletromagnetismo

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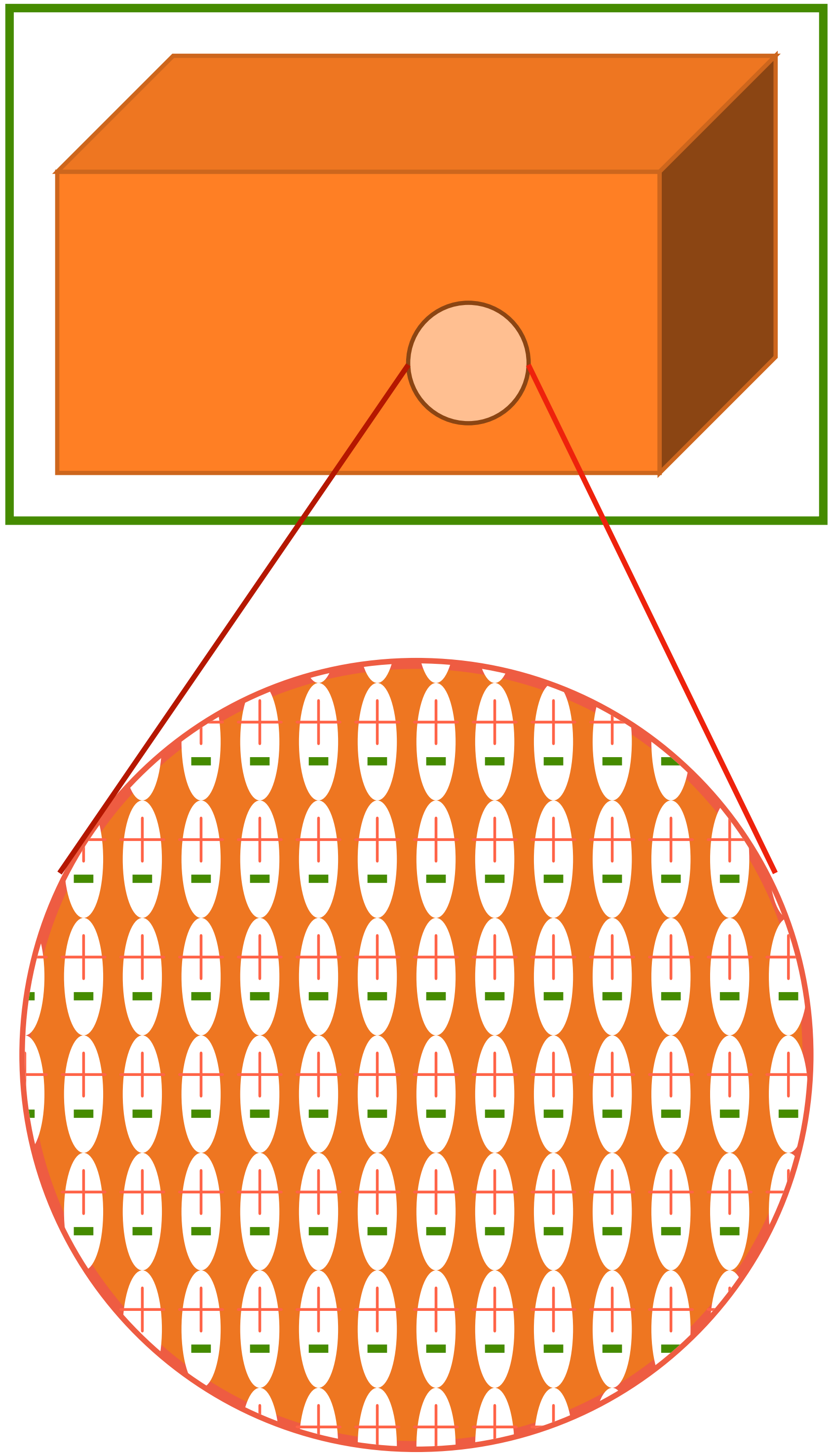
$$\vec{\nabla} \times \vec{H} = \vec{j} + \epsilon_0 \frac{\partial \vec{D}}{\partial t}$$

Dielétricos

Polarização

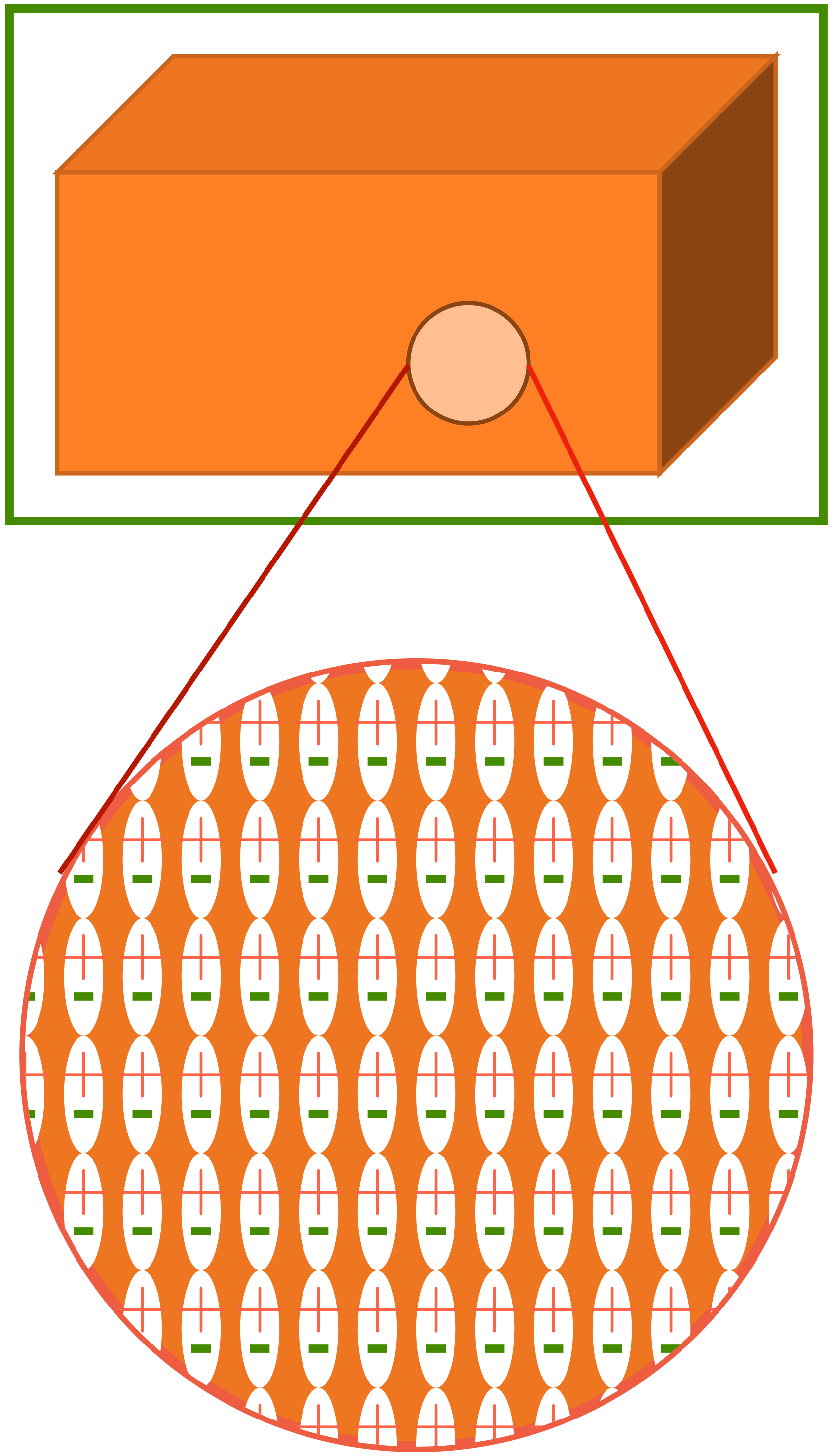
$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\frac{\vec{p}\cdot\hat{\mathscr{r}}}{\mathscr{r}^2}$$



Polarização

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\frac{\vec{p}\cdot\hat{\mathscr{r}}}{\mathscr{r}^2}$$

$$\vec{P} = \frac{\sum_j \vec{p_j}}{\Delta\tau}$$ (Polarização)



Polarização

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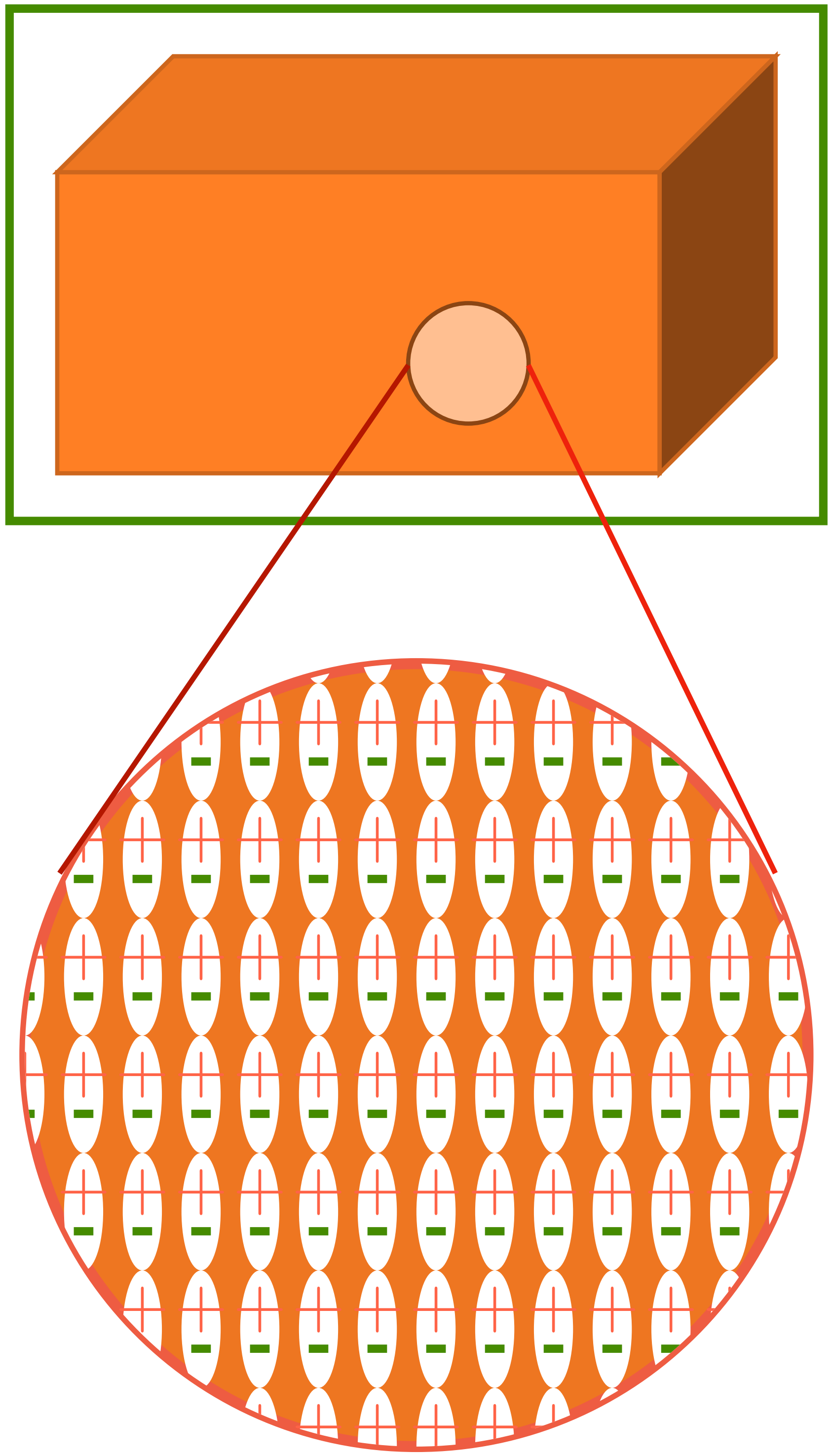
$$\vec{P} = \frac{\sum_j \vec{p_j}}{\Delta\tau}$$

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\int \frac{\hat{\mathscr{r}}\cdot\vec{P}(\vec{r'})}{\mathscr{r}^2}\,\mathrm{d}\tau'$$



Polarização

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\frac{\vec{p}\cdot\hat{\mathcal{r}}}{\mathcal{r}^2}$$

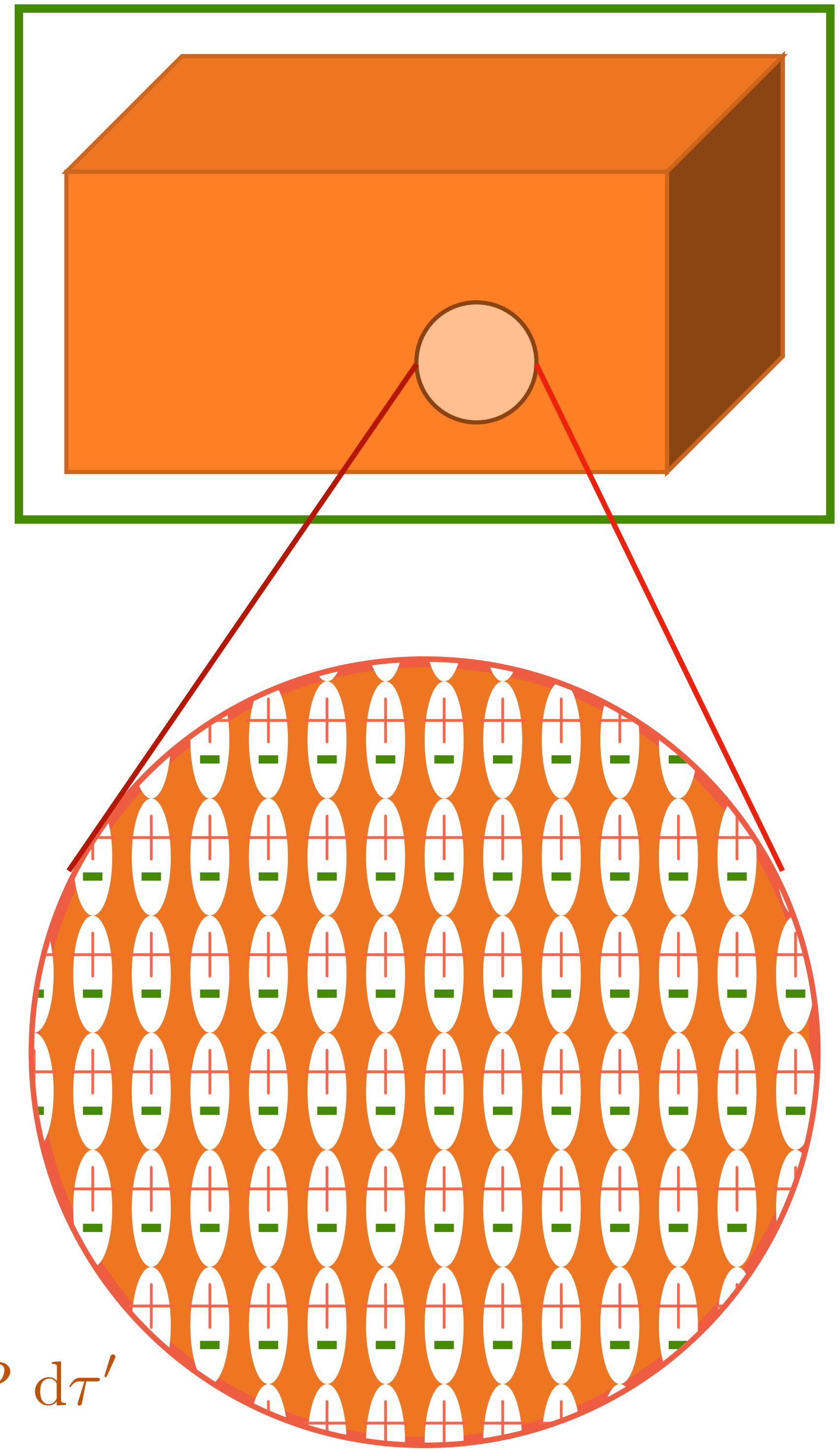
$$\vec{P} = \frac{\sum_j \vec{p_j}}{\Delta\tau}$$

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\int \frac{\hat{\mathcal{r}}\cdot\vec{P}(\vec{r'})}{\mathcal{r}^2}\, d\tau'$$

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\int \vec{P}(\vec{r'})\cdot\vec{\nabla}'\left(\frac{1}{\mathcal{r}}\right) d\tau'$$

$$\vec{\nabla}'\cdot\left(\frac{\vec{P}}{\mathcal{r}}\right) = \frac{1}{\mathcal{r}}\vec{\nabla}'\cdot\vec{P} + \vec{P}\cdot\vec{\nabla}'\left(\frac{1}{\mathcal{r}}\right)$$

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\int \vec{\nabla}'\cdot\left(\frac{\vec{P}(\vec{r'})}{\mathcal{r}}\right) d\tau' - \frac{1}{4\pi\epsilon_0}\int \frac{1}{\mathcal{r}}\vec{\nabla}'\cdot P\, d\tau'$$



Polarização

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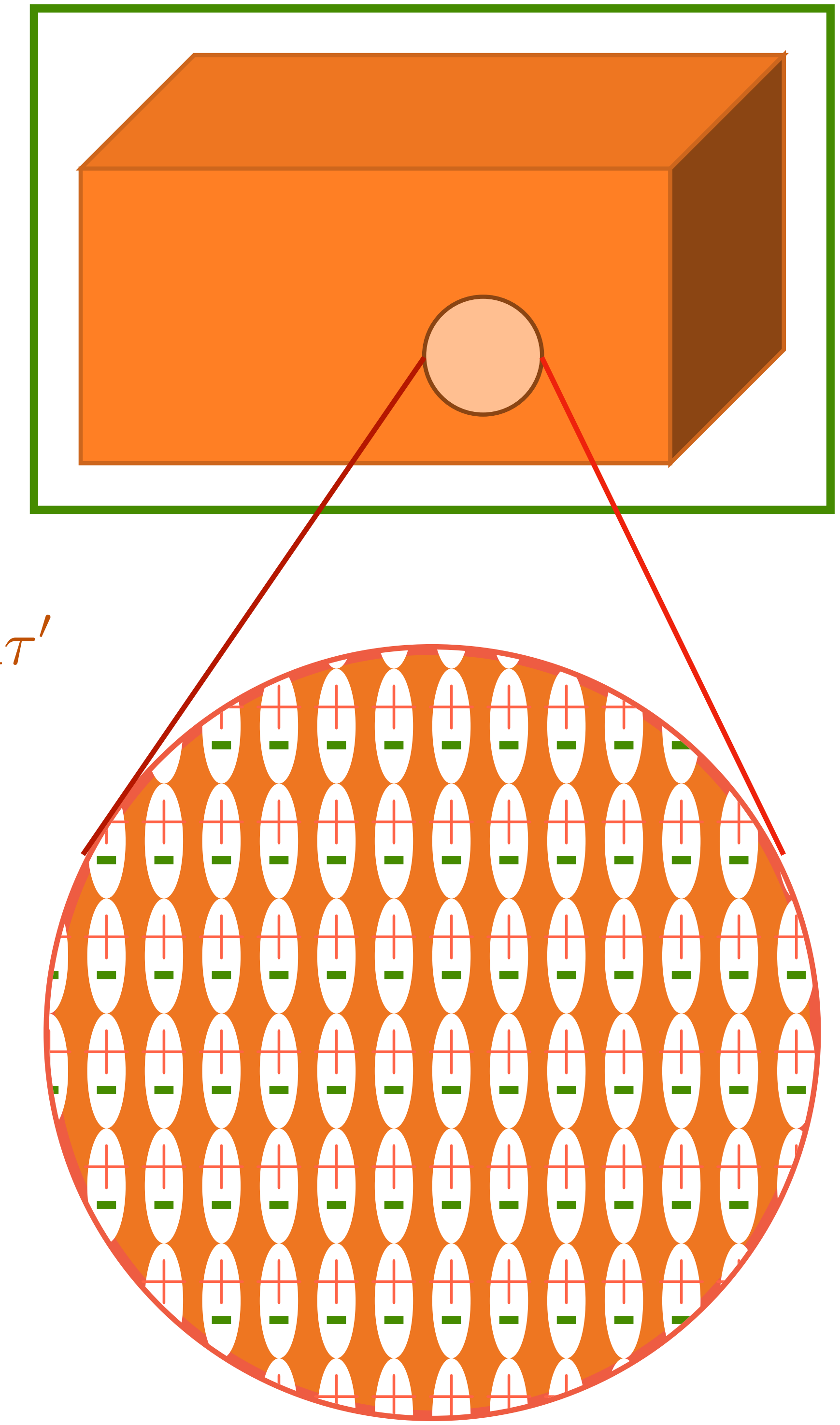
$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\int \vec{\nabla}'\cdot\left(\frac{\vec{P}(\vec{r'})}{\mathscr{r}}\right)\,\mathrm{d}\tau' - \frac{1}{4\pi\epsilon_0}\int \frac{1}{\mathscr{r}}\vec{\nabla}'\cdot P\,\mathrm{d}\tau'$$



Polarização

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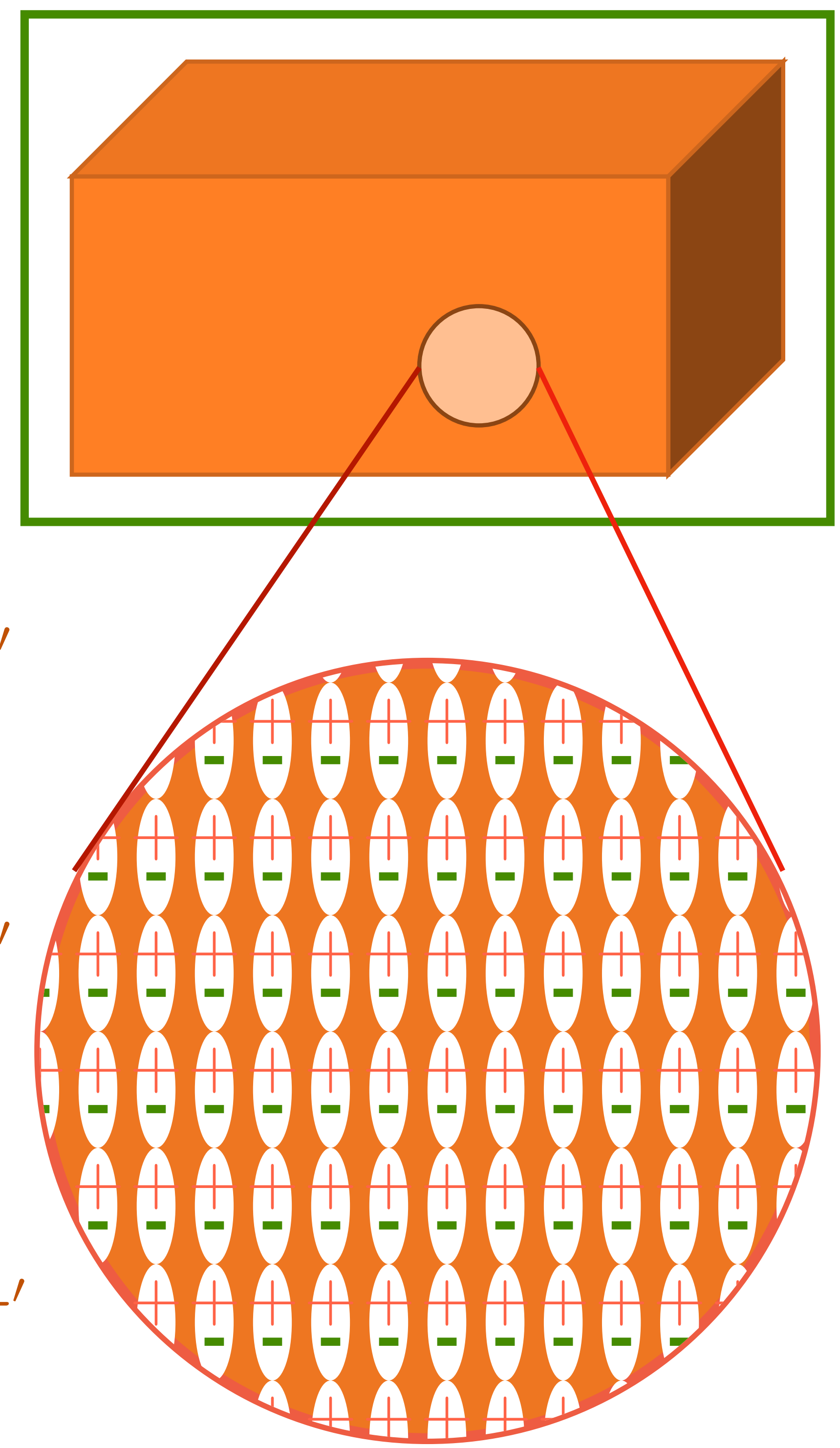

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\int_S \frac{1}{\mathscr{r}}\vec{P}(\vec{r'})\cdot\hat{n}\ \mathrm{d}\tau' - \frac{1}{4\pi\epsilon_0}\int \frac{1}{\mathscr{r}}\vec{\nabla}'\cdot\vec{P}\ \mathrm{d}\tau'$$

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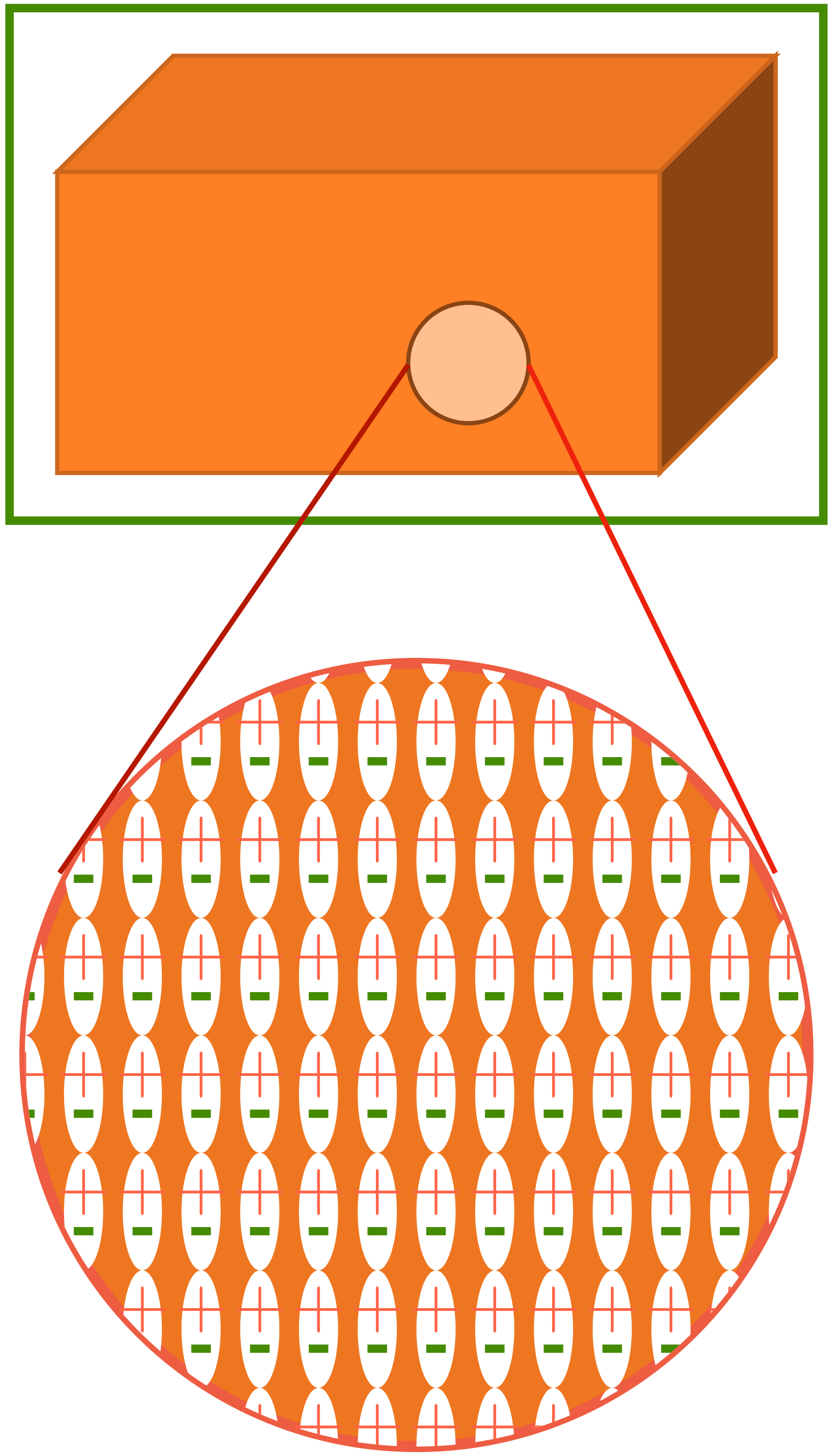
$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\int_{\mathcal{S}} \frac{1}{\mathscr{r}}\vec{P}(\vec{r'})\cdot\hat{n}\ \mathrm{d}A - \frac{1}{4\pi\epsilon_0}\int_{\mathcal{V}} \frac{1}{\mathscr{r}}\vec{\nabla}'\cdot\vec{P}\ \mathrm{d}\tau'$$

Polarização

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\int_{\mathcal{S}} \frac{1}{\mathscr{r}}\vec{P}(\vec{r'})\cdot\hat{n}\;\mathrm{d}A - \frac{1}{4\pi\epsilon_0}\int_{\mathcal{V}} \frac{1}{\mathscr{r}}\vec{\nabla}'\cdot\vec{P}\;\mathrm{d}\tau'$$

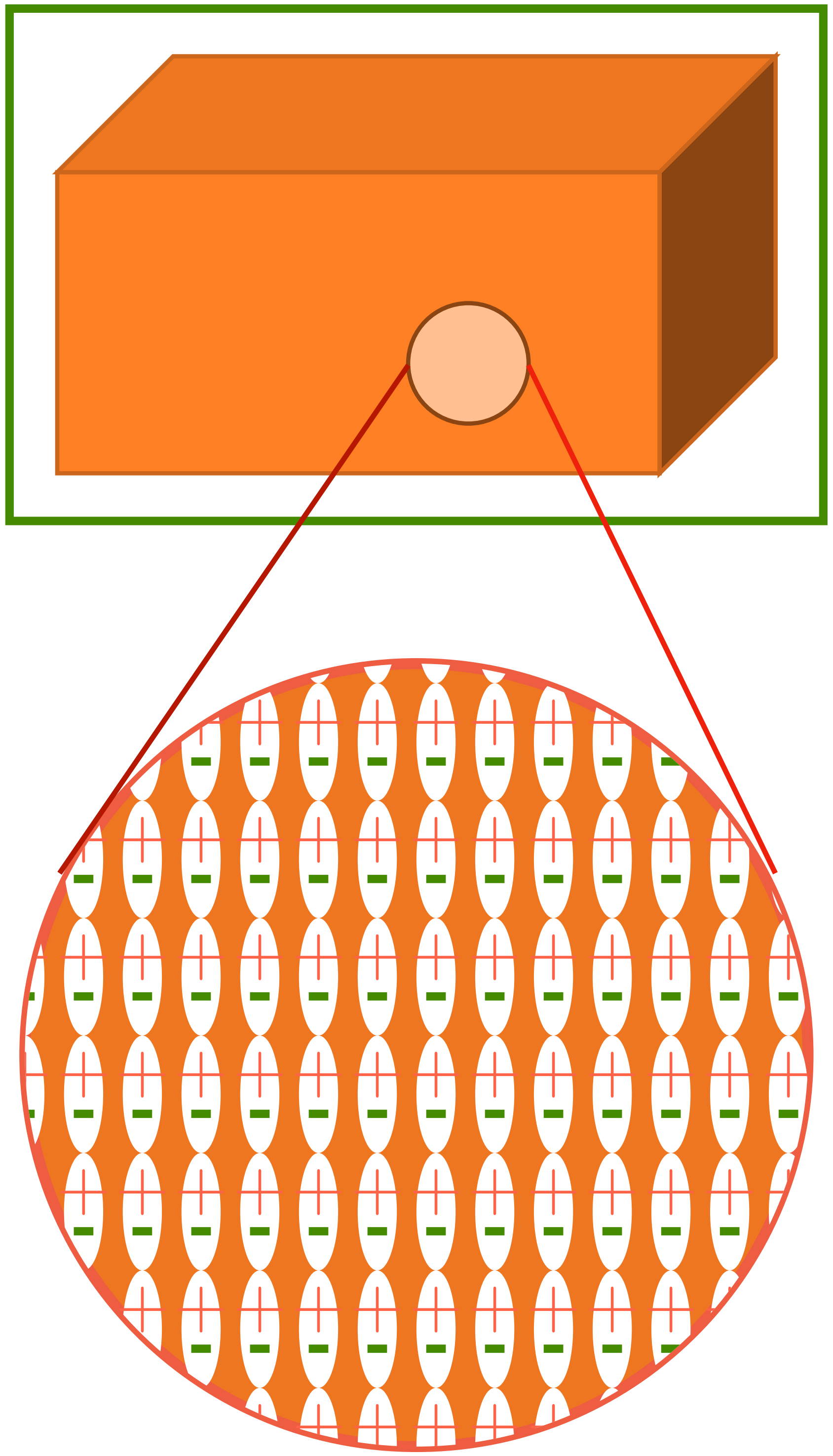


Polarização

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\int_{\mathcal{S}} \frac{1}{\mathscr{r}}\vec{P}(\vec{r'})\cdot\hat{n}\ \mathrm{d}A - \frac{1}{4\pi\epsilon_0}\int_{\mathcal{V}} \frac{1}{\mathscr{r}}\vec{\nabla}'\cdot\vec{P}\ \mathrm{d}\tau'$$

$$\sigma_b \equiv \vec{P}\cdot\hat{n}$$

$$\rho_b \equiv -\vec{\boldsymbol{\nabla}}\cdot\vec{P}$$



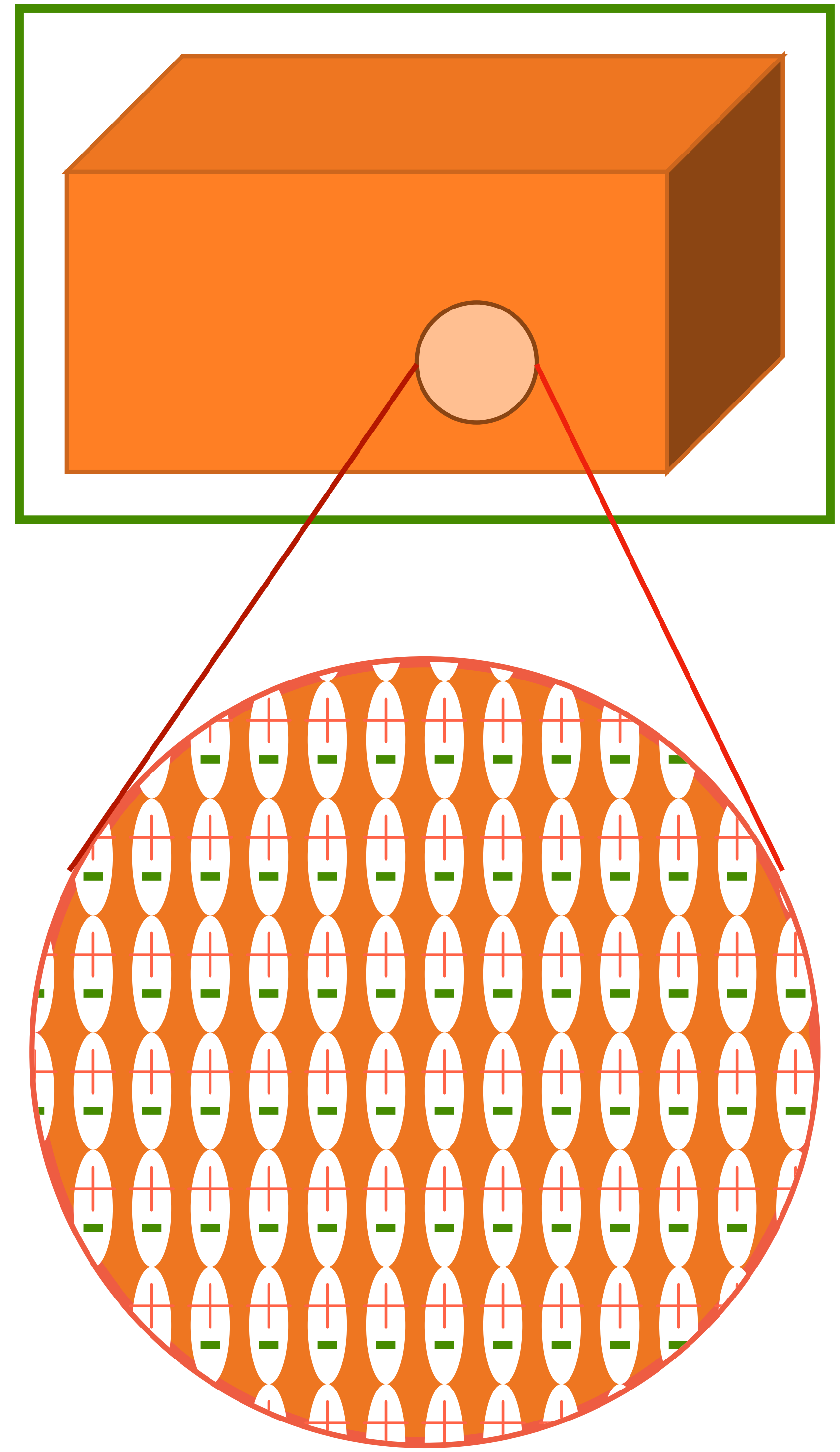
Polarização

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0} \int_{\mathcal{S}} \frac{1}{\mathcal{r}} \vec{P}(\vec{r'}) \cdot \hat{n} \, \mathrm{d}A - \frac{1}{4\pi\epsilon_0} \int_{\mathcal{V}} \frac{1}{\mathcal{r}} \vec{\nabla}' \cdot \vec{P} \, \mathrm{d}\tau'$$

$$\sigma_b \equiv \vec{P} \cdot \hat{n}$$

$$\rho_b \equiv -\vec{\boldsymbol{\nabla}} \cdot \vec{P}$$

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0} \int_{\mathcal{S}} \frac{\sigma_b}{\mathcal{r}} \, \mathrm{d}A' + \frac{1}{4\pi\epsilon_0} \int_{\mathcal{V}} \frac{\rho_b}{\mathcal{r}} \, \mathrm{d}\tau'$$



Polarização

Interpretação física

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0}\int_{\mathcal{S}} \frac{\sigma_b}{\mathscr{r}}\, \mathrm{d}A' + \frac{1}{4\pi\epsilon_0}\int_{\mathcal{V}} \frac{\rho_b}{\mathscr{r}}\, \mathrm{d}\tau'$$

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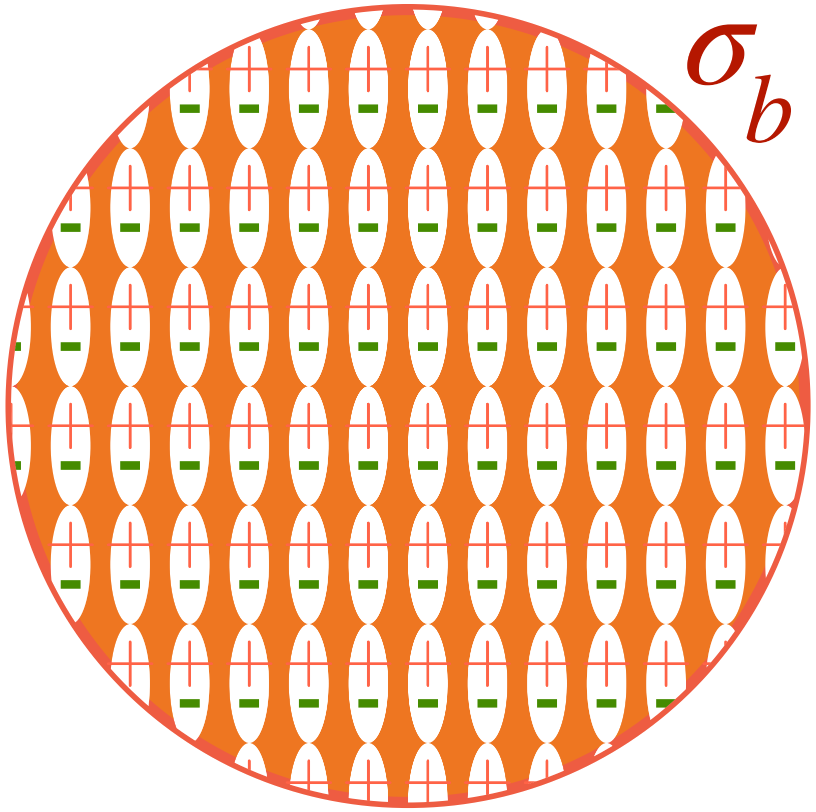

Polarização

Interpretação física

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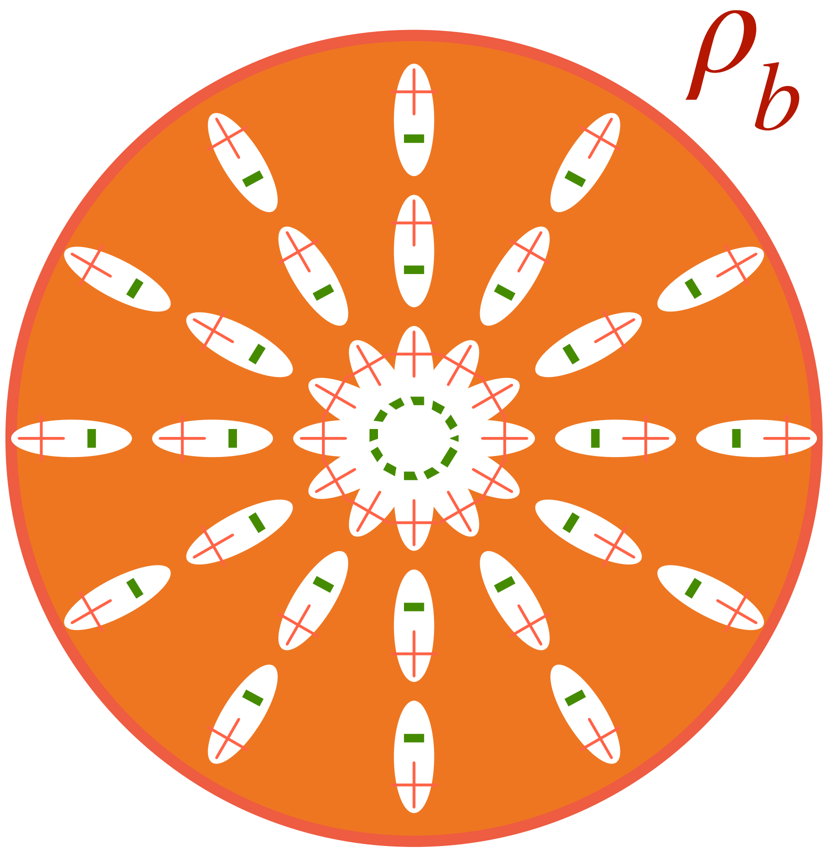
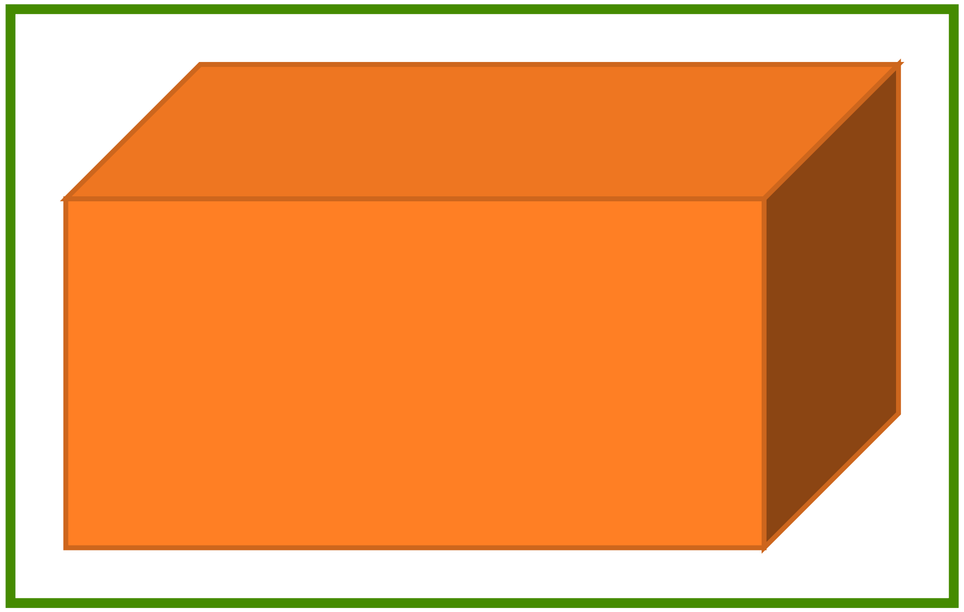


Vetor deslocamento

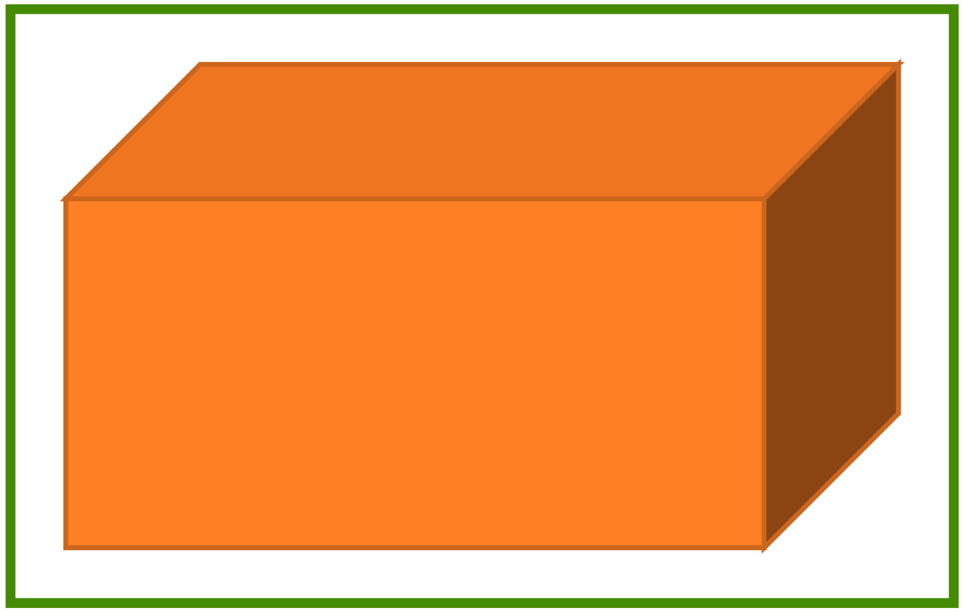
$$\rho = \rho_f + \rho_b$$



Vetor deslocamento

$$\rho = \rho_f + \rho_b$$

$$\epsilon_0 \vec{\nabla} \cdot \vec{E} = \rho_f + \rho_b$$



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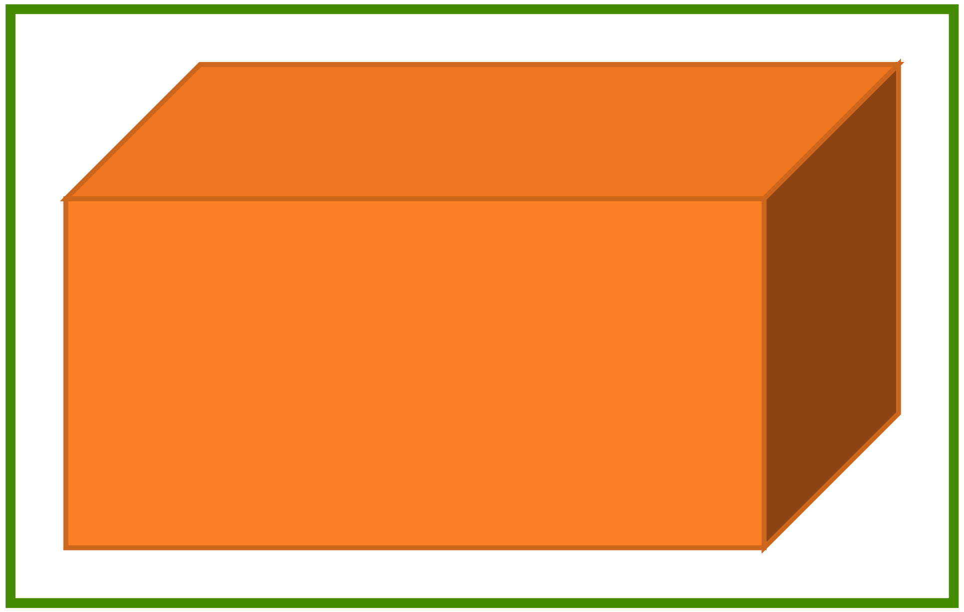

$$\epsilon_0 \vec{\boldsymbol{\nabla}} \cdot \vec{E} = \rho_f + \rho_b$$

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Vetor deslocamento

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$$\epsilon_0 \vec{\nabla} \cdot \vec{E} = \rho_f + \rho_b$$

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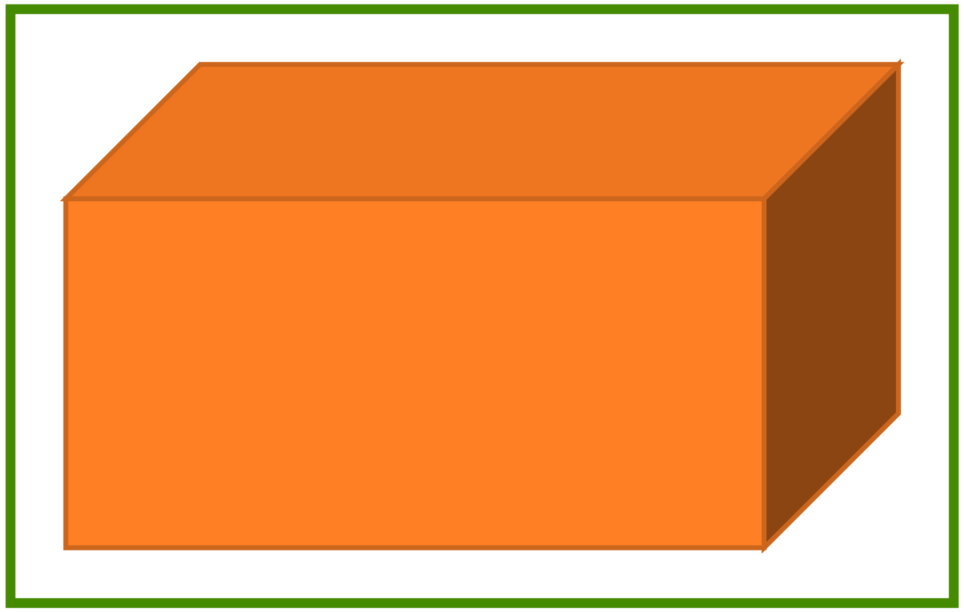

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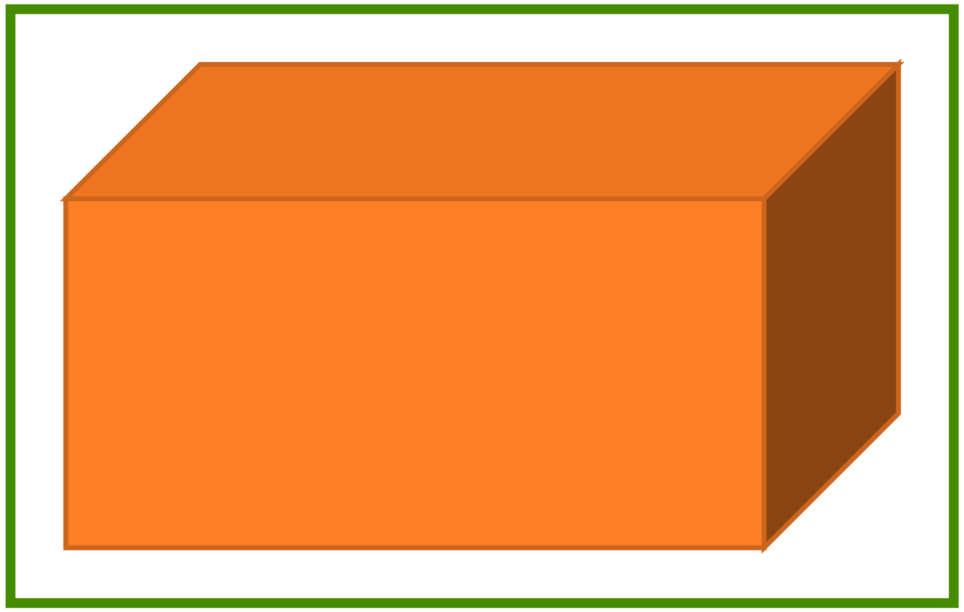

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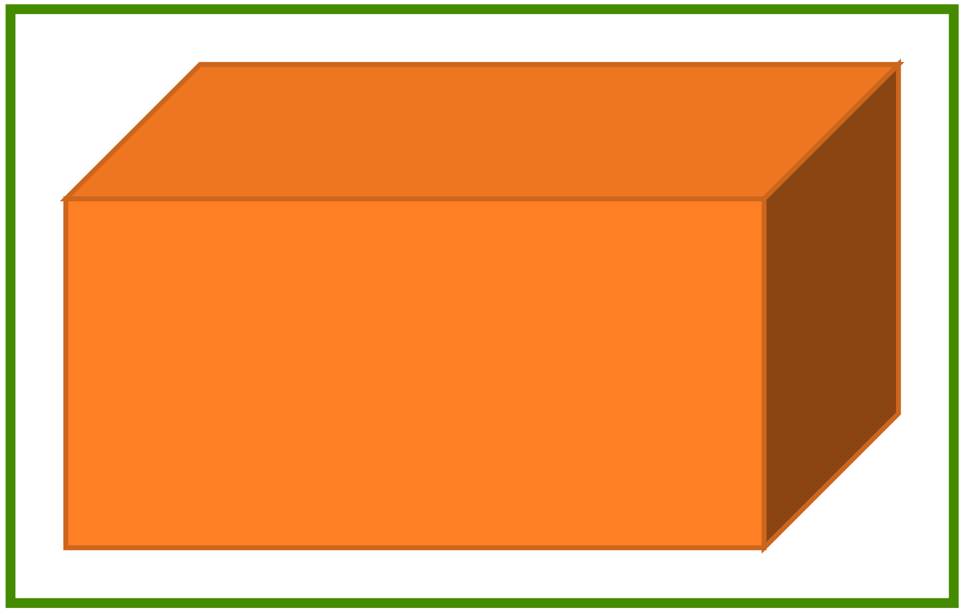
$$\epsilon_0 \vec{\nabla} \cdot \vec{E} = \rho_f + \rho_b$$

$$\epsilon_0 \vec{\nabla} \cdot \vec{E} = \rho_f - \vec{\nabla} \cdot \vec{P}$$

$$\vec{\nabla} \cdot \left(\epsilon_0 \vec{E} + \vec{P}\right) = \rho_f$$

Vetor deslocamento

$$\rho = \rho_f + \rho_b$$



$$\epsilon_0 \vec{\nabla} \cdot \vec{E} = \rho_f + \rho_b$$

$$\epsilon_0 \vec{\nabla} \cdot \vec{E} = \rho_f - \vec{\nabla} \cdot \vec{P}$$

$$\rho_b \equiv -\vec{\nabla} \cdot \vec{P}$$

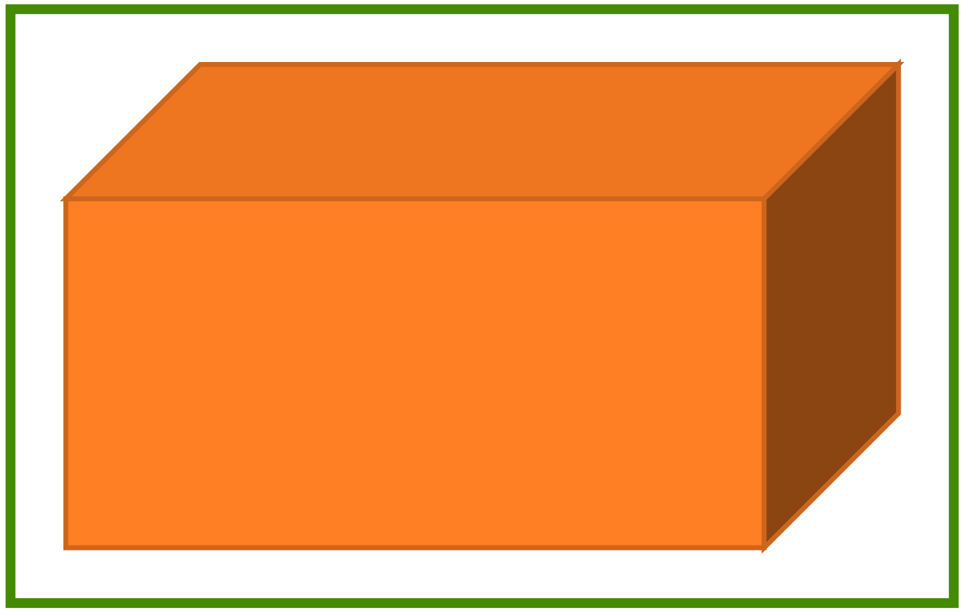
$$\vec{\nabla} \cdot \left(\epsilon_0 \vec{E} + \vec{P} \right) = \rho_f$$

$$\vec{D} \equiv \epsilon_0 \vec{E} + \vec{P}$$

$$\vec{\nabla} \cdot \vec{D} = \rho_f$$

Vetor deslocamento

$$\rho = \rho_f + \rho_b$$



$$\rho_b \equiv -\vec{\nabla} \cdot \vec{P}$$

$$\epsilon_0 \vec{\nabla} \cdot \vec{E} = \rho_f + \rho_b$$

$$\epsilon_0 \vec{\nabla} \cdot \vec{E} = \rho_f - \vec{\nabla} \cdot \vec{P}$$

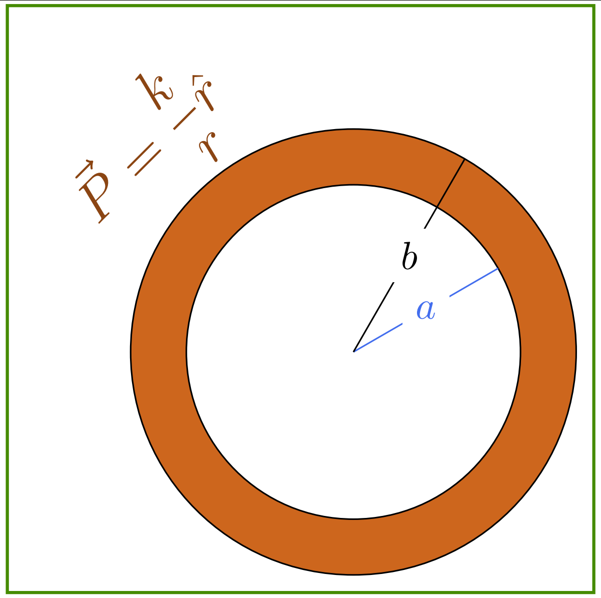
$$\vec{\nabla} \cdot \left(\epsilon_0 \vec{E} + \vec{P} \right) = \rho_f$$

$$\vec{D} \equiv \epsilon_0 \vec{E} + \vec{P}$$

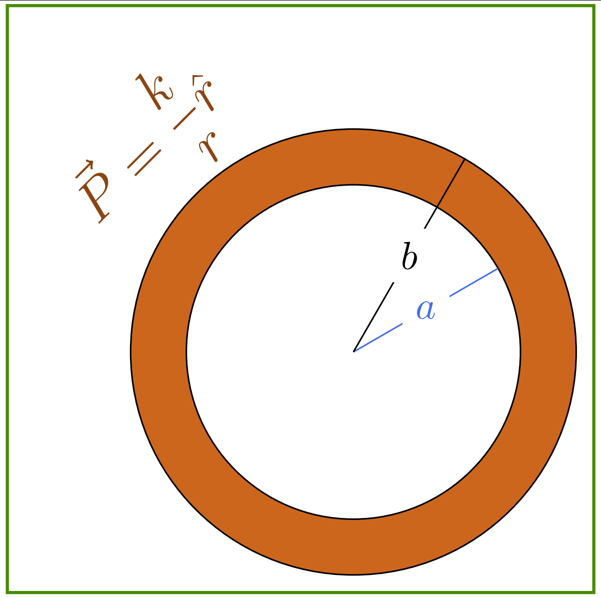
$$\boxed{\vec{\nabla} \cdot \vec{D} = \rho_f} \qquad \int_{\mathcal{A}} \vec{D} \cdot \hat{n} \, \mathrm{d}A = Q_f$$

Pratique o que aprendeu

$$\vec{E} = ?$$



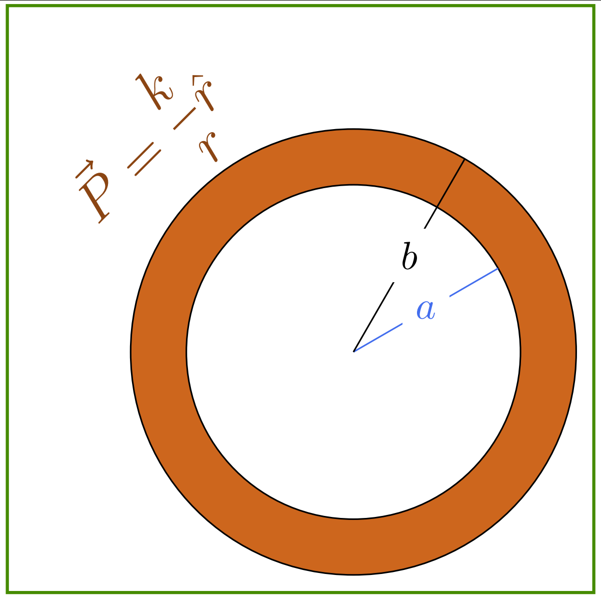
Pratique o que aprendeu



$$\vec{E} = ?$$

$$\vec{D} = 0$$

Pratique o que aprendeu

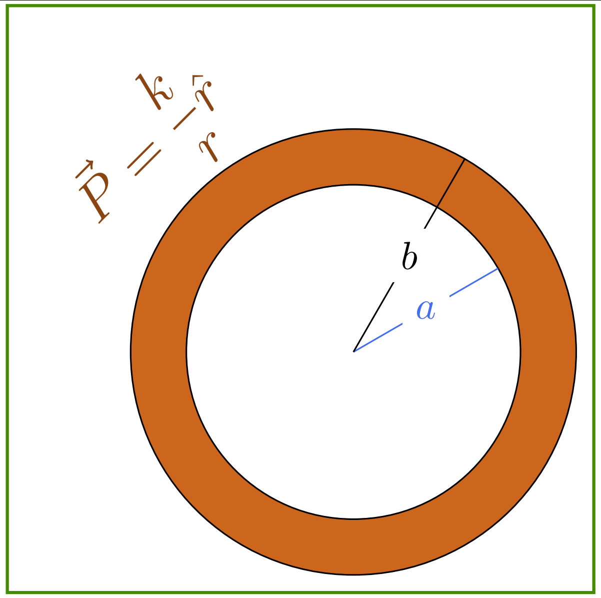


$$\vec{E} = ?$$

$$\vec{D} = 0$$

$$\Rightarrow \epsilon_0 \vec{E} + \vec{P} = 0$$

Pratique o que aprendeu



$$\vec{E} = ?$$

$$\vec{D} = 0$$

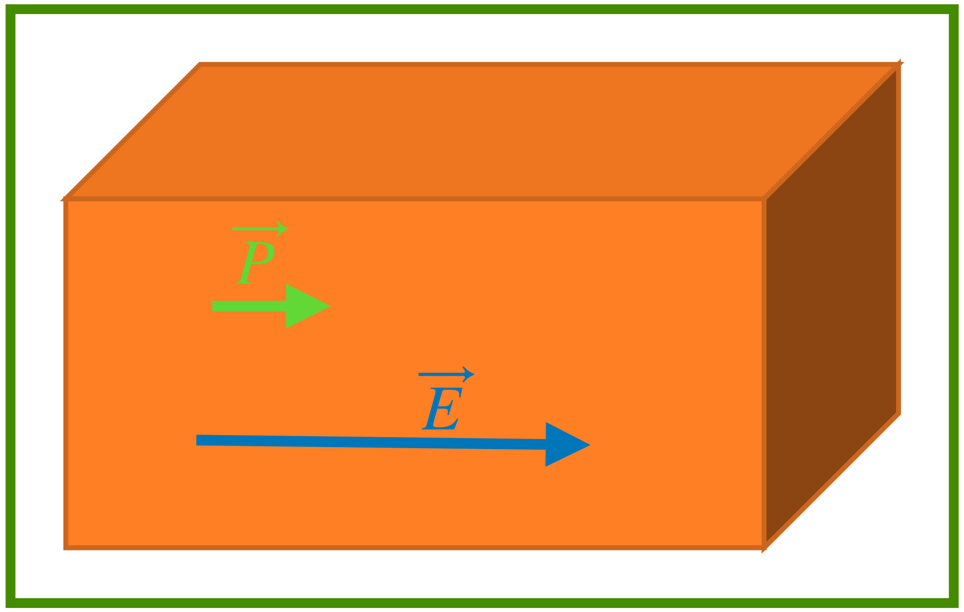
$$\Rightarrow \epsilon_0 \vec{E} + \vec{P} = 0$$

$$\Rightarrow \begin{cases} \vec{E} = 0 & (r < a \quad \text{e} \quad r > b) \\ \vec{E} = -\dfrac{k}{\epsilon_0 r}\hat{r} & (a < r < b) \end{cases}$$

Meios lineares

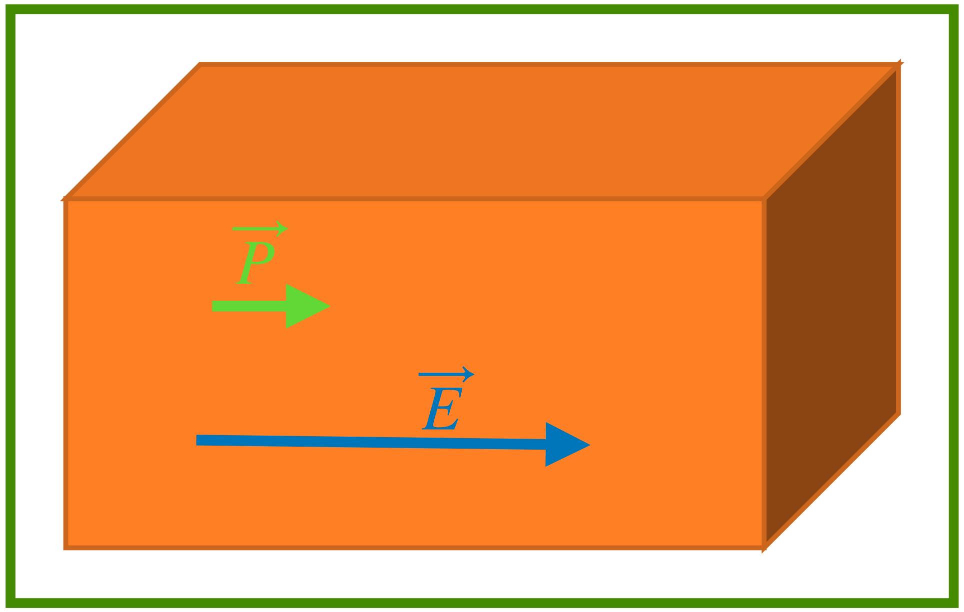
$$\vec{P} = \chi_e \epsilon_0 \vec{E}$$

Susceptibilidade



Meios lineares

$$\vec{P} = \chi_e \epsilon_0 \vec{E}$$

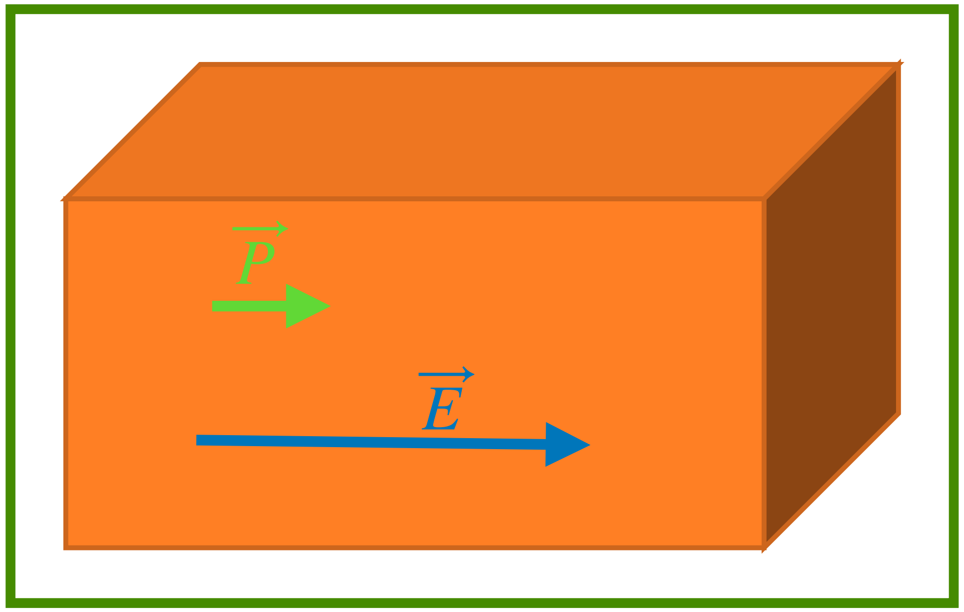


Susceptibilidade

$$\vec{D} = \epsilon_0 \vec{E} + \chi_e \epsilon_0 \vec{E}$$

Meios lineares

$\vec{P} = \chi_e \epsilon_0 \vec{E}$ Susceptibilidade



$\vec{D} = \epsilon_0 \vec{E} + \chi_e \epsilon_0 \vec{E}$

$\vec{D} = (1 + \chi_0)\epsilon_0 \vec{E}$

$\epsilon = (1 + \chi_0)\epsilon_0$ Permissividade

$\epsilon_r = 1 + \chi_0$ Constante dielétrica

$\vec{D} = \epsilon \vec{E} = \epsilon_r \epsilon_0 \vec{E}$

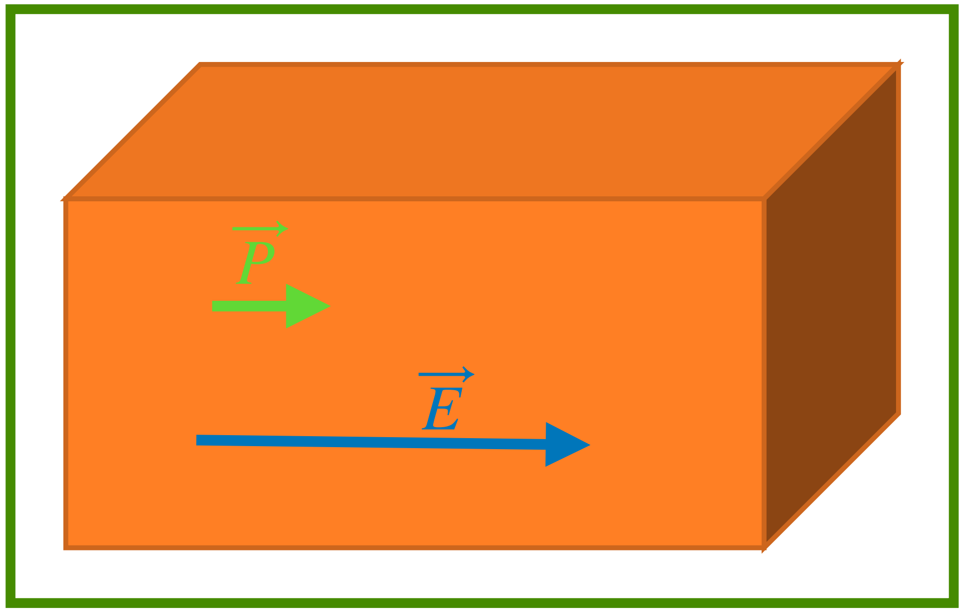
Meios lineares

$$\vec{P} = \chi_e \epsilon_0 \vec{E}$$

Susceptibilidade

$$\vec{D} = \epsilon \vec{E} = \epsilon_r \epsilon_0 \vec{E}$$

$$\epsilon_r = 1 + \chi_0$$



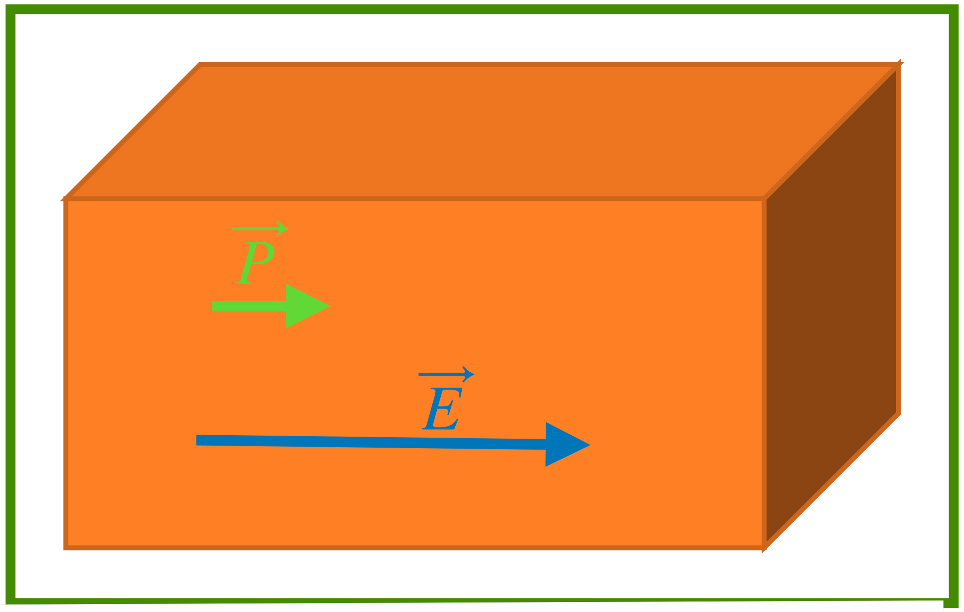
Meios lineares

$$\vec{P} = \chi_e \epsilon_0 \vec{E}$$

Susceptibilidade

$$\vec{D} = \epsilon \vec{E} = \epsilon_r \epsilon_0 \vec{E}$$

$$\epsilon_r = 1 + \chi_0$$



Material	Dielectric Constant	Material	Dielectric Constant
Vacuum	1	Benzene	2.28
Helium	1.000065	Diamond	5.7
Neon	1.00013	Salt	5.9
Hydrogen	1.00025	Silicon	11.8
Argon	1.00052	Methanol	33.0
Air (dry)	1.00054	Water	80.1
Nitrogen	1.00055	Ice (-30° C)	99
Water vapor (100° C)	1.00587	$KTaNbO_3$ (0° C)	34,000

Pratique o que aprendeu

$$\vec{E} = ?$$