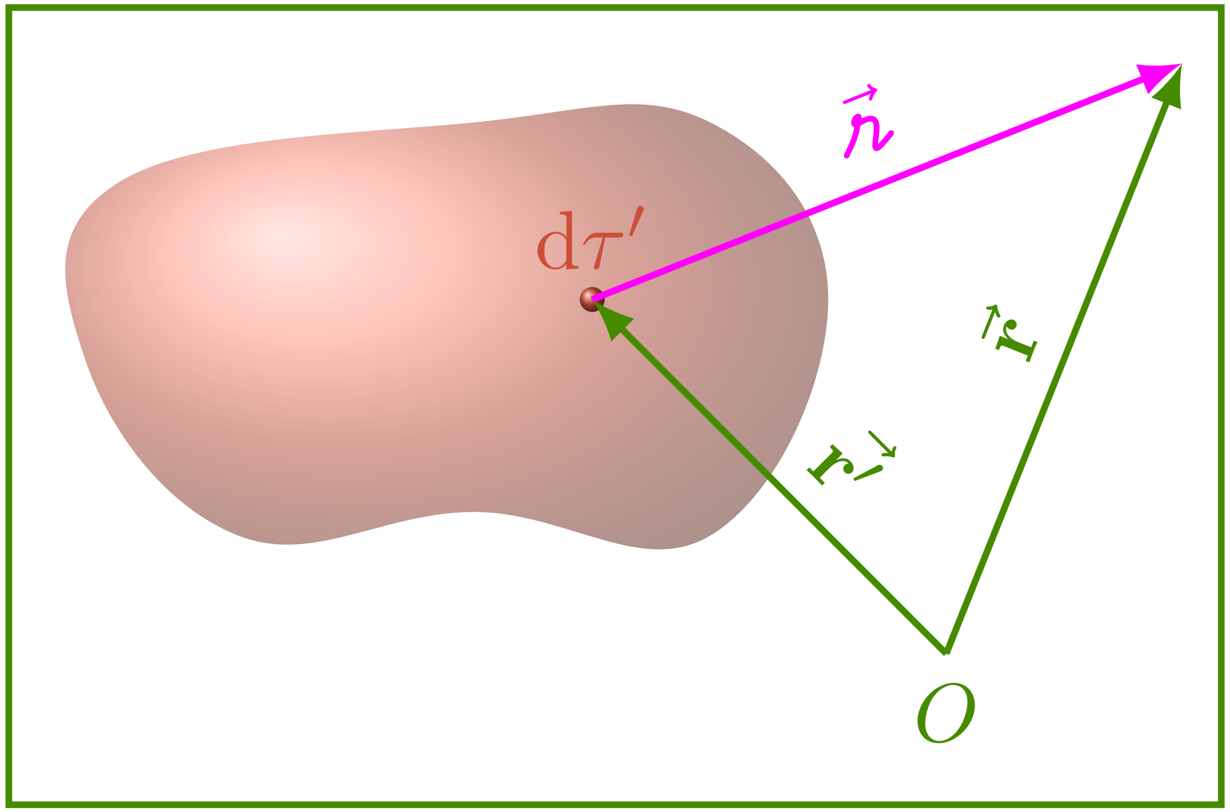
Eletromagnetismo Avançado

3º ciclo
Aula de 10 de novembro

Potencial e potencial vetor

$$\Box^2 V = -\frac{\rho}{\epsilon_0}$$

$$V(\vec{\mathbf{r}}, t) = \frac{1}{4\pi\epsilon_0}\int \frac{\rho(\vec{\mathbf{r}'}, t_r)}{\mathscr{r}}\, \mathrm{d}\tau'$$

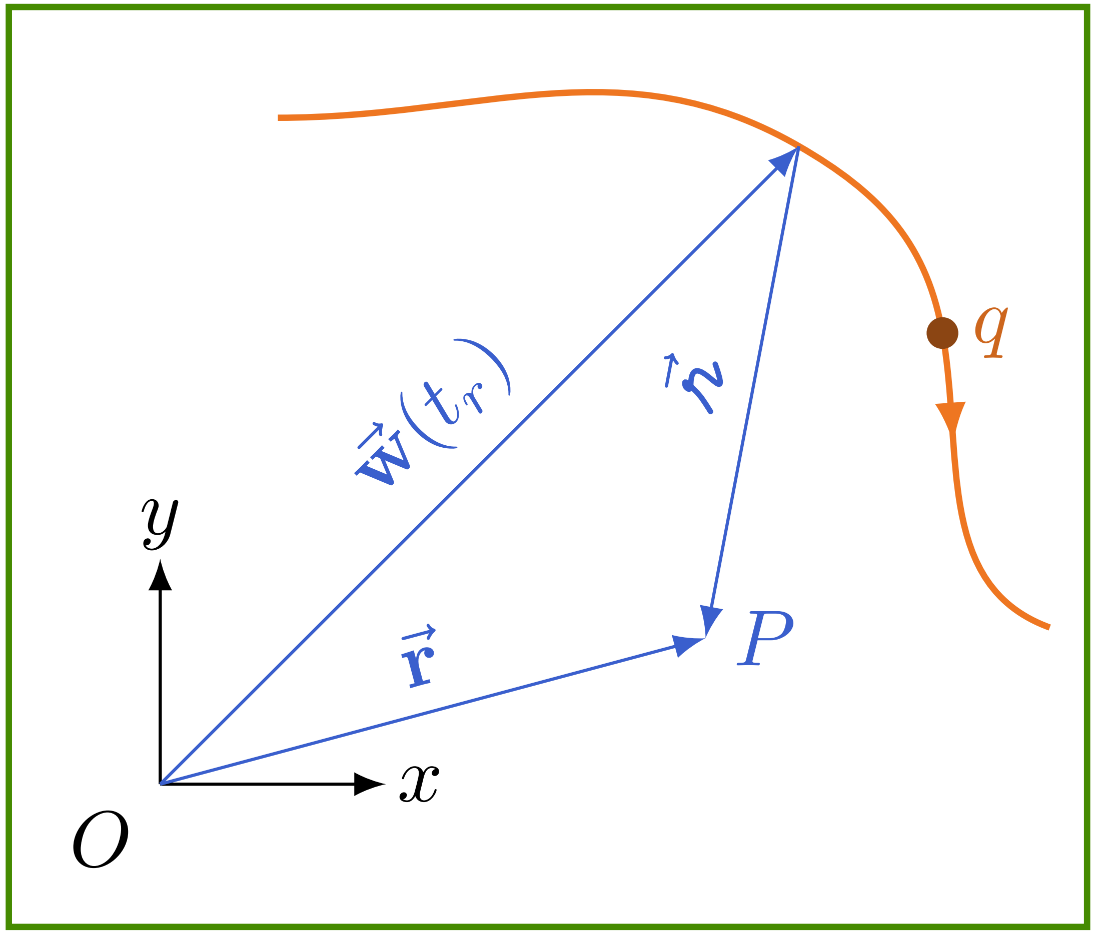


$$t_r \equiv t - \frac{\mathscr{r}}{c}$$

$$\Box^2 \vec{\mathbf{A}} = -\mu_0 \vec{\mathbf{J}}$$

$$\vec{\mathbf{A}}(\vec{\mathbf{r}}, t) = \frac{\mu_0}{4\pi}\int \frac{\vec{\mathbf{J}}(\vec{\mathbf{r}'}, t_r)}{\mathscr{r}}\, \mathrm{d}\tau'$$

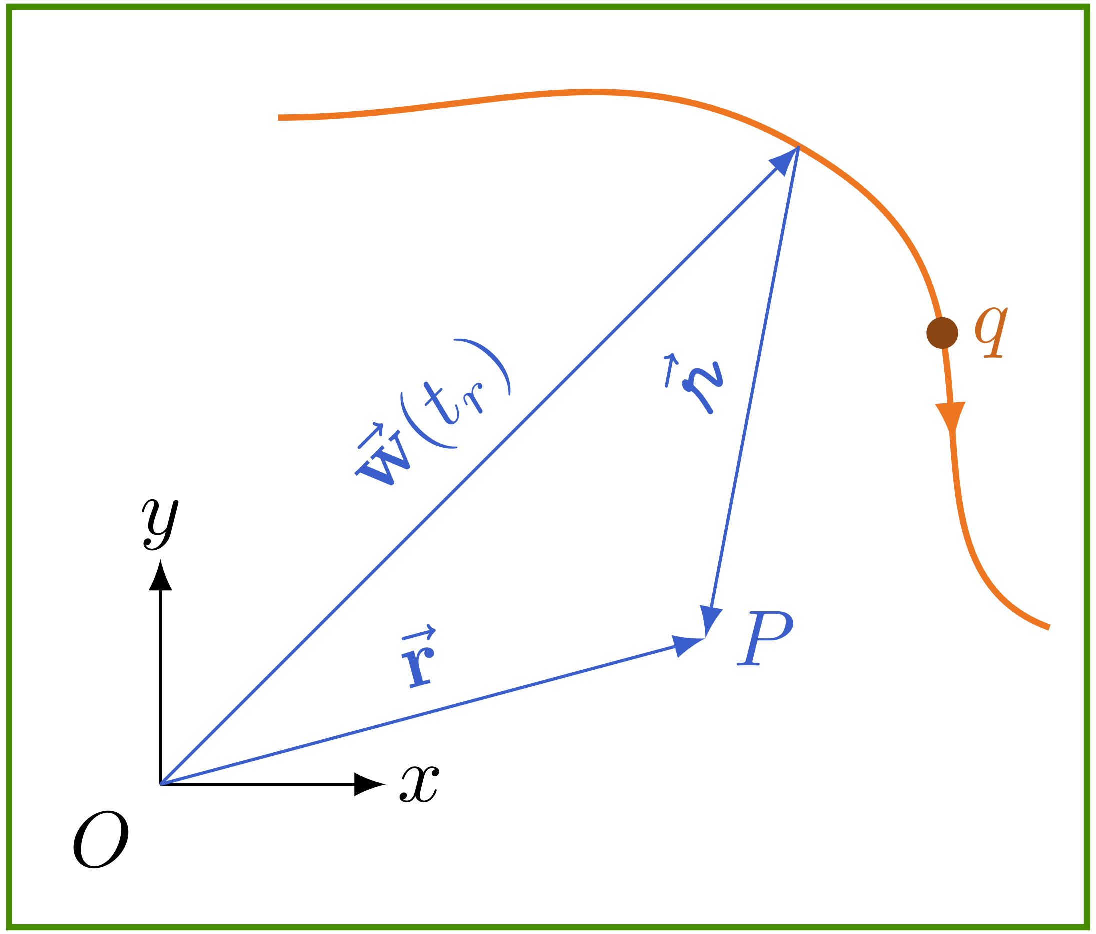
Potenciais de Liénard e Wiechert



Potenciais de Liénard e Wiechert

$$V(\vec{\mathbf{r}}, t) = \frac{1}{4\pi\epsilon_0} \frac{q}{\mathscr{r} - \vec{\mathscr{r}} \cdot \frac{\vec{\mathbf{v}}}{c}}$$

$$\vec{\mathbf{A}}(\vec{\mathbf{r}}, t) = \frac{\mu_0}{4\pi} \frac{q\vec{\mathbf{v}}}{\mathscr{r} - \vec{\mathscr{r}} \cdot \frac{\vec{\mathbf{v}}}{c}}$$



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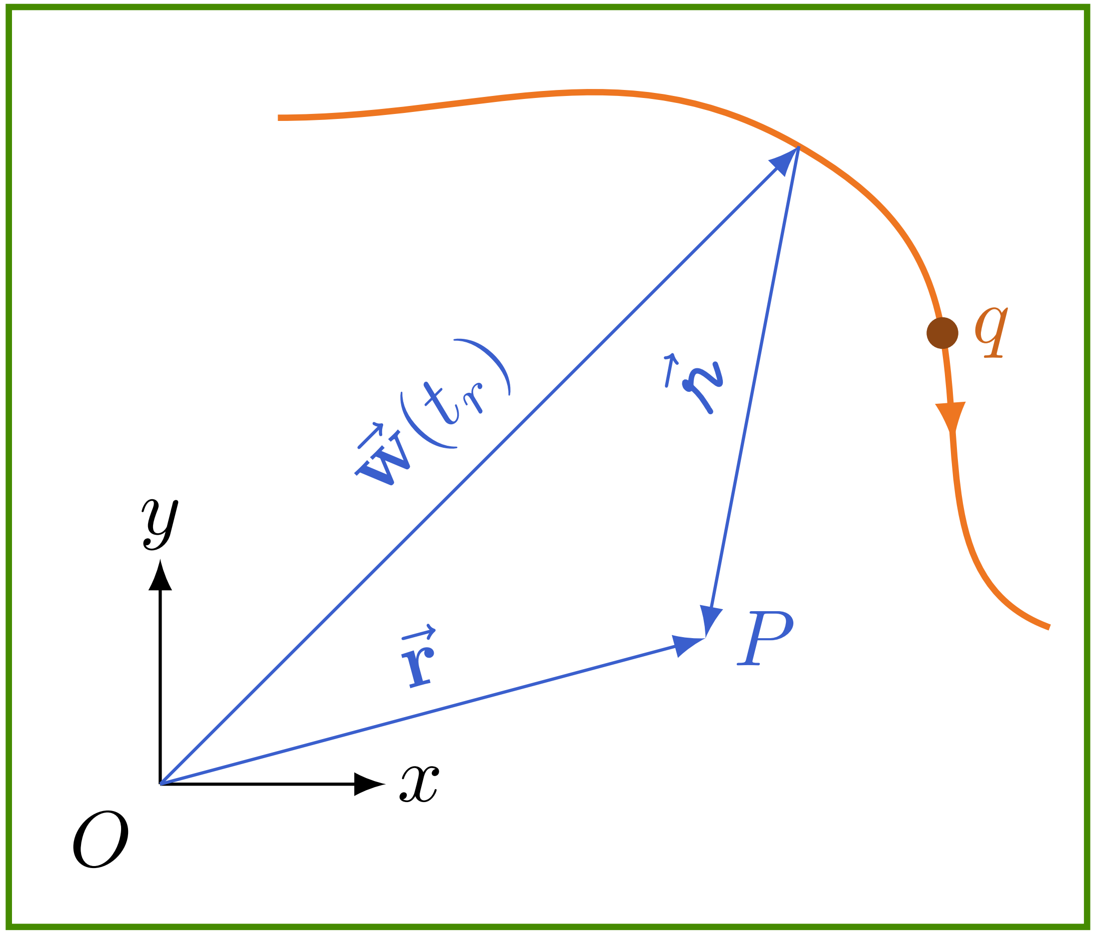
$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = ?$$



Potenciais de Liénard e Wiechert

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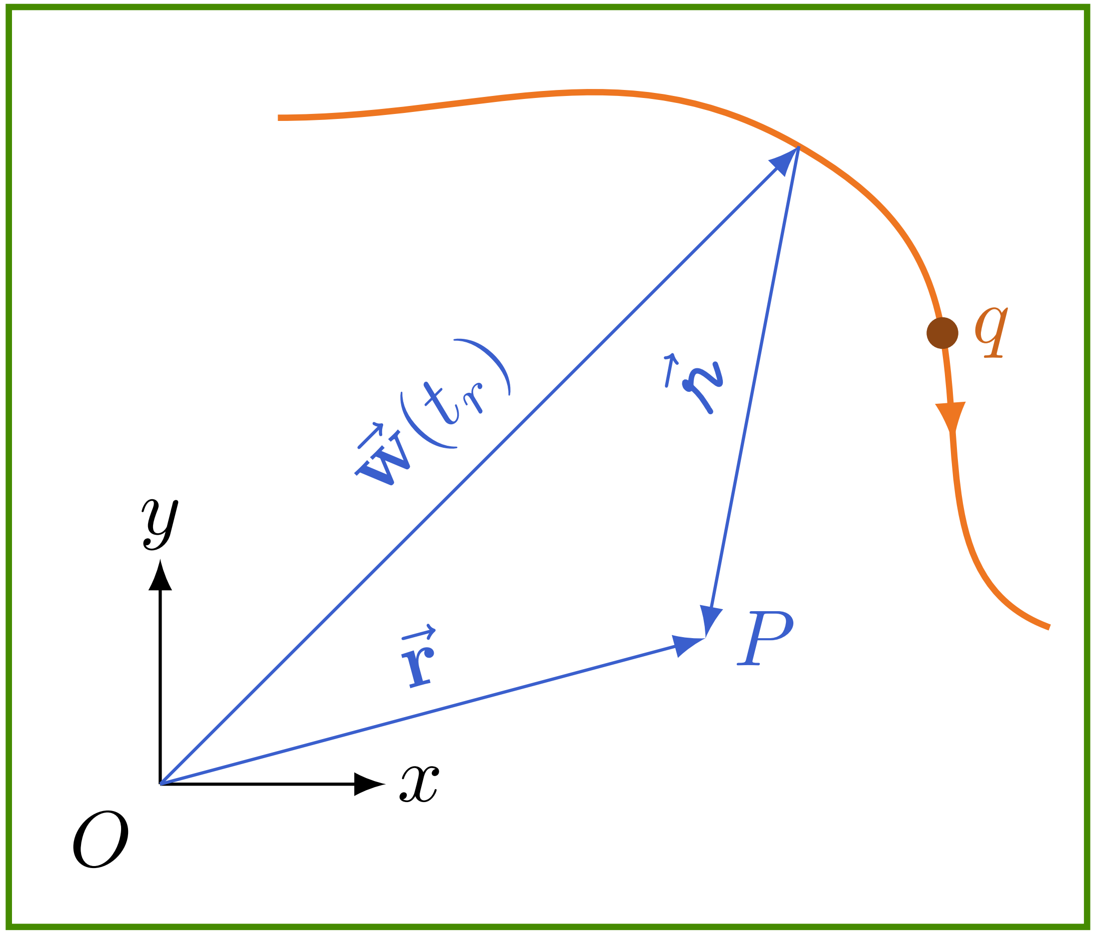
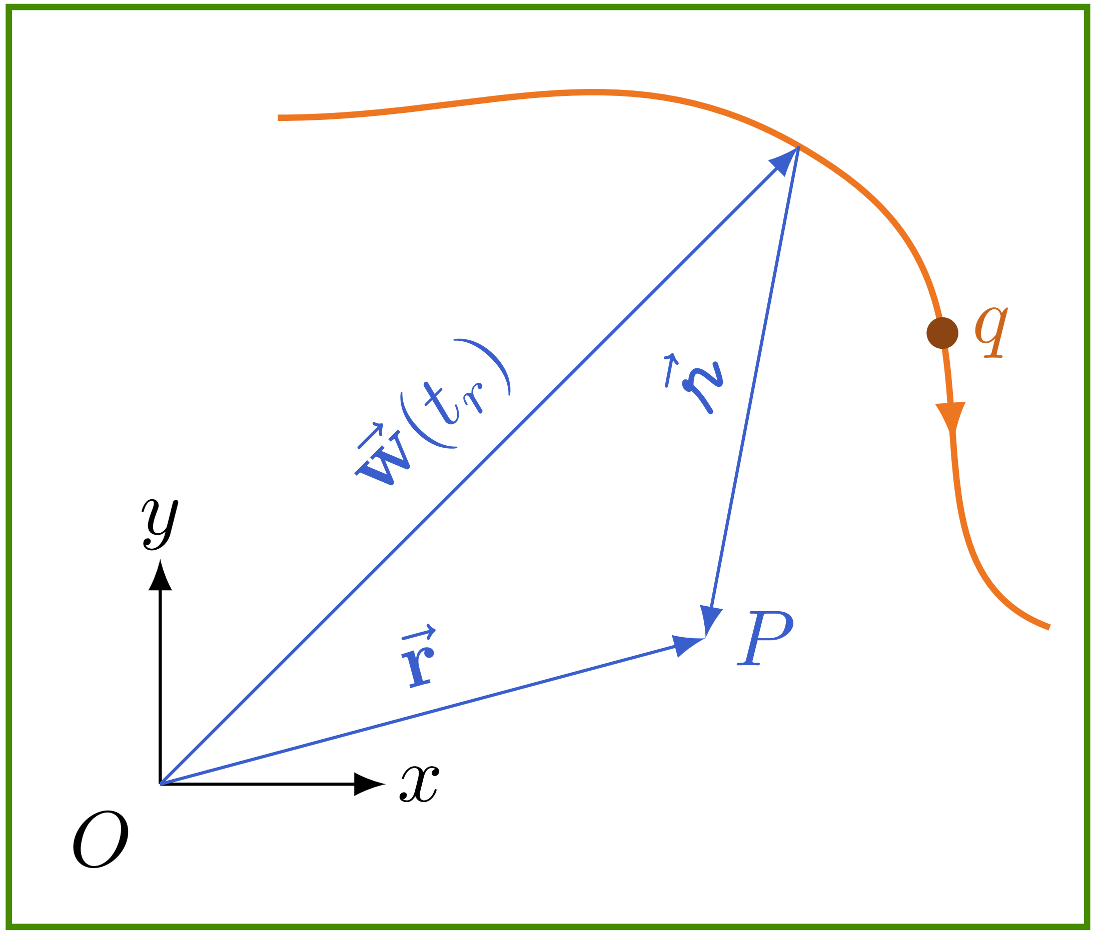


Potenciais de Liénard e Wiechert

$$V(\vec{\mathbf{r}},t) = \frac{1}{4\pi\epsilon_0}\frac{qc}{\vec{\boldsymbol{\mathscr{r}}}\cdot\vec{\mathbf{u}}}$$

$$\vec{\mathbf{A}}(\vec{\mathbf{r}},t) = \frac{\vec{\mathbf{v}}}{c^2}V(\vec{\mathbf{r}},t)$$

$$\vec{\mathbf{u}} \equiv c\hat{\boldsymbol{\mathscr{r}}} - \vec{\mathbf{v}}$$



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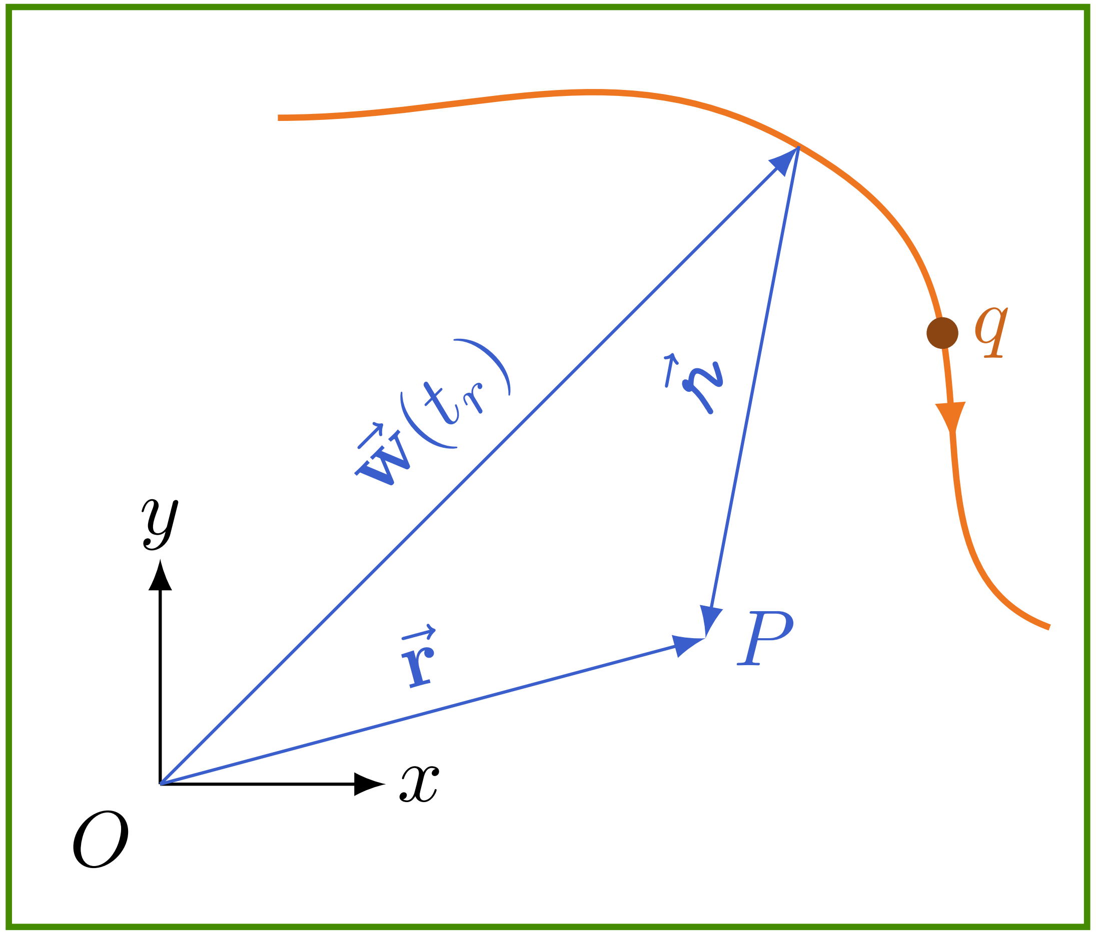
$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = -\vec{\boldsymbol{\nabla}} V - \frac{\partial \vec{\mathbf{A}}}{\partial t}$$



Potenciais de Liénard e Wiechert

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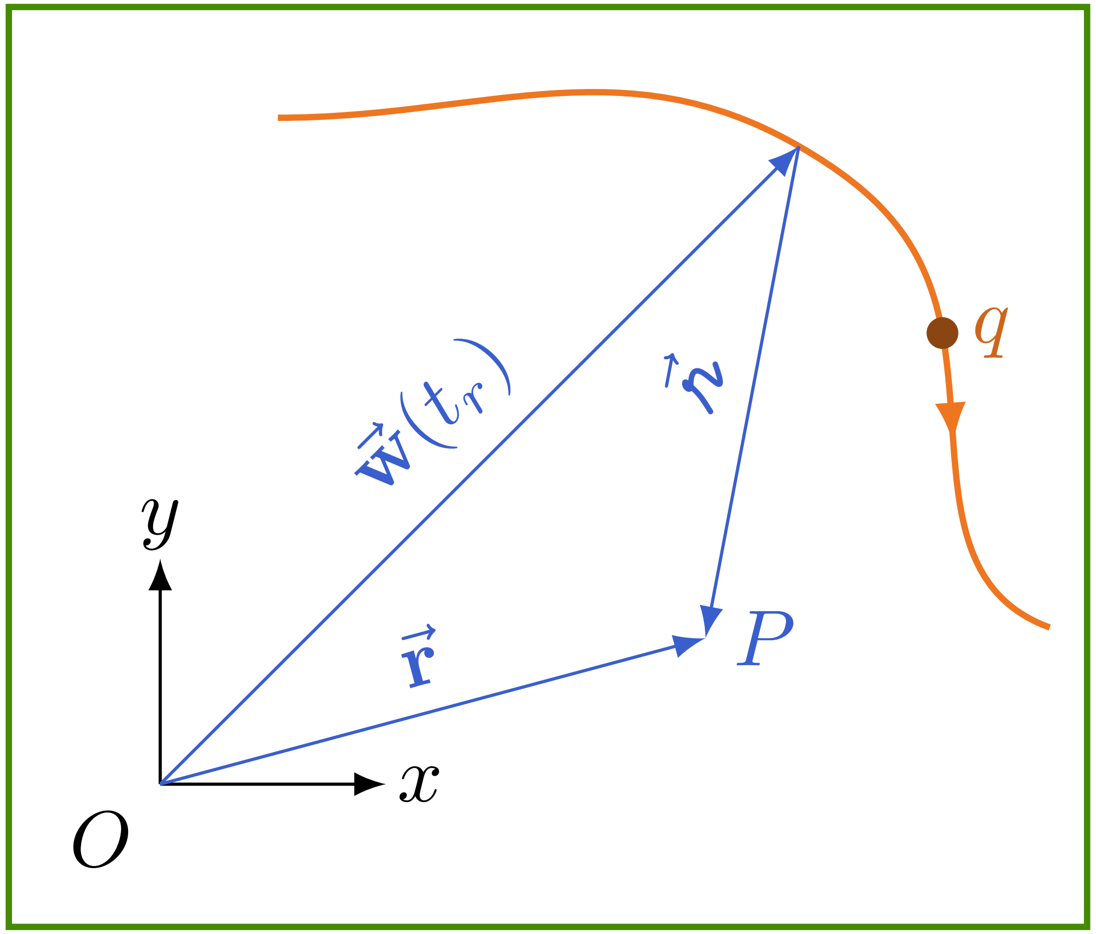

$$\vec{\mathbf{A}}(\vec{\mathbf{r}}, t) = \frac{\vec{\mathbf{v}}}{c^2}V(\vec{\mathbf{r}}, t)$$

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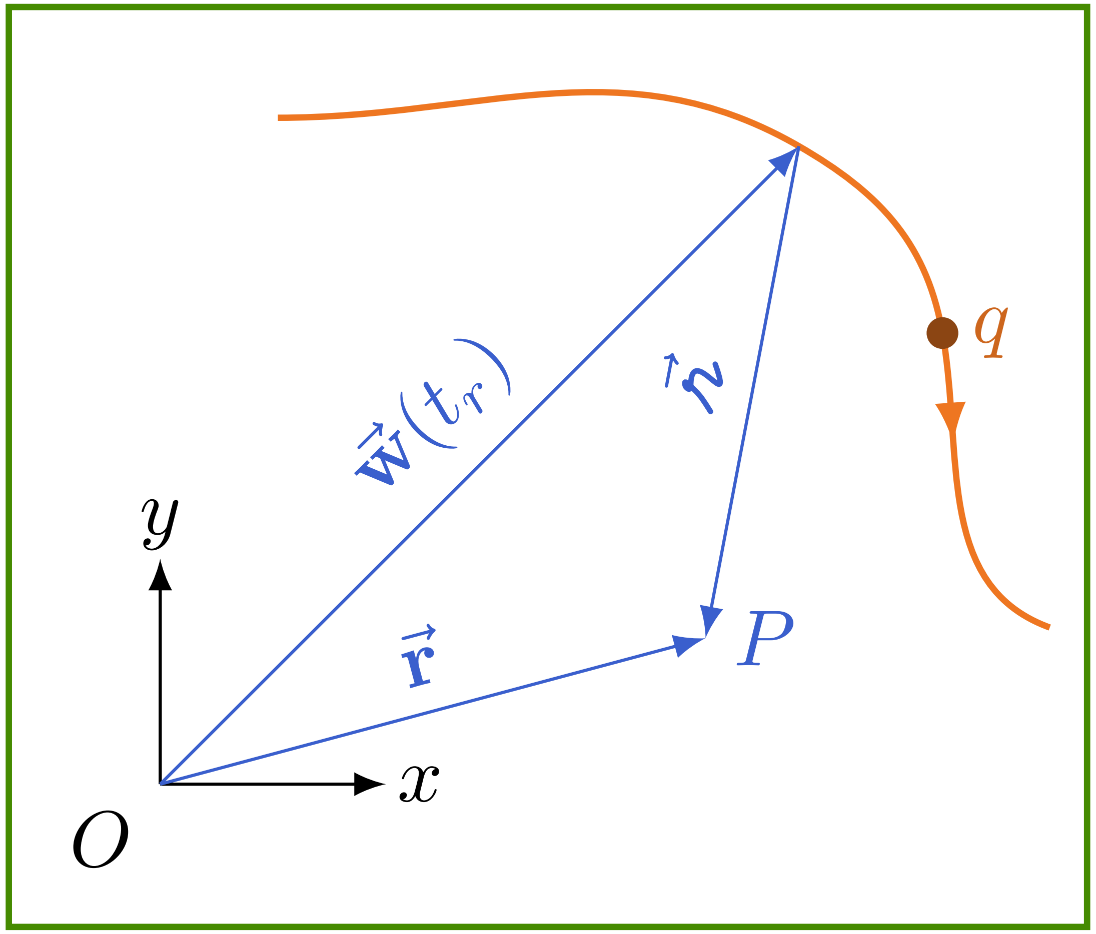
$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = -\vec{\boldsymbol{\nabla}}V - \frac{\partial \vec{\mathbf{A}}}{\partial t}$$

$$\vec{\boldsymbol{\nabla}}V = \frac{qc}{4\pi\epsilon_0}\frac{-1}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^2}\vec{\boldsymbol{\nabla}}(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})$$

Potenciais de Liénard e Wiechert

$$V(\vec{\mathbf{r}}, t) = \frac{1}{4\pi\epsilon_0} \frac{qc}{\vec{\mathscr{r}} \cdot \vec{\mathbf{u}}}$$



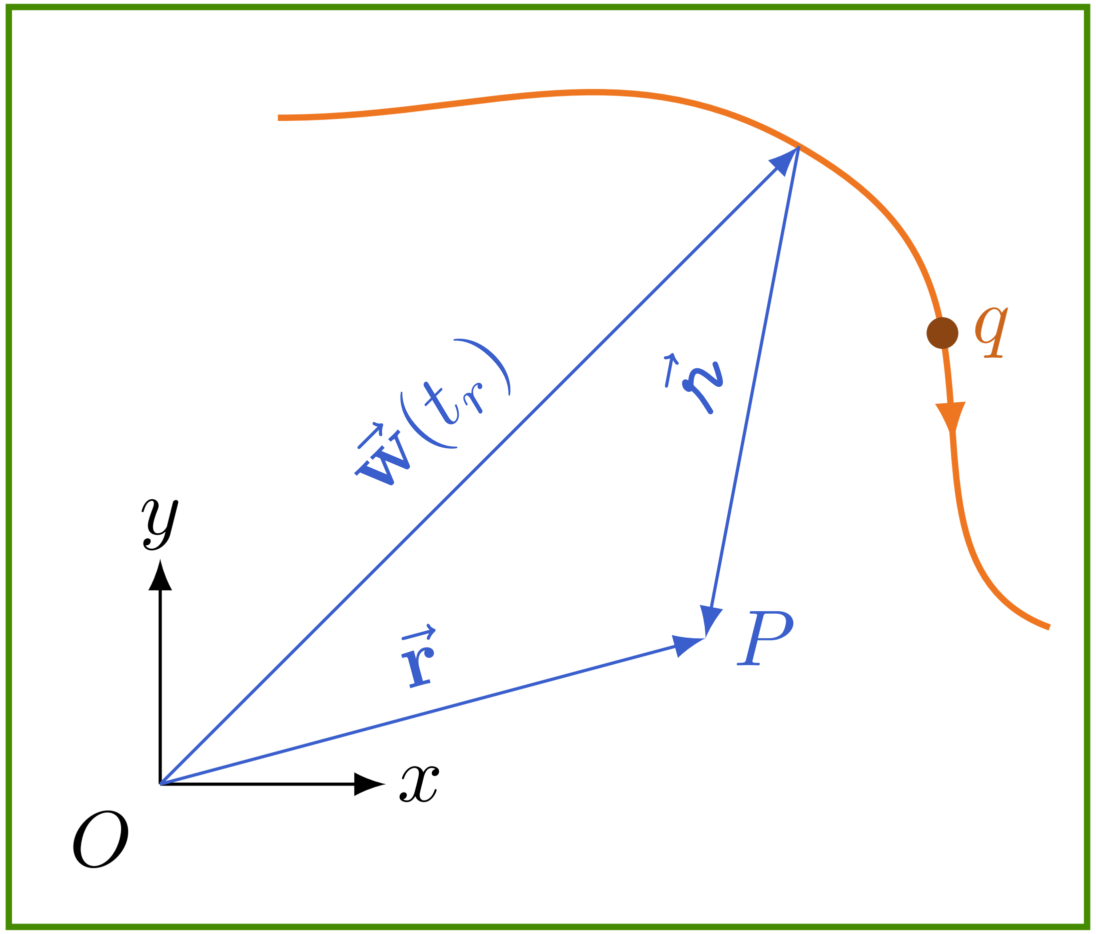
$$\vec{\mathbf{A}}(\vec{\mathbf{r}}, t) = \frac{\vec{\mathbf{v}}}{c^2} V(\vec{\mathbf{r}}, t)$$

$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = -\vec{\boldsymbol{\nabla}} V - \frac{\partial \vec{\mathbf{A}}}{\partial t}$$

$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3} [(c^2 - v^2)\vec{\mathbf{u}} + \vec{\mathscr{r}} \times (\vec{\mathbf{u}} \times \vec{\mathbf{a}})]$$

Potenciais de Liénard e Wiechert

$$V(\vec{\mathbf{r}}, t) = \frac{1}{4\pi\epsilon_0} \frac{qc}{\vec{\mathscr{r}} \cdot \vec{\mathbf{u}}}$$



$$\vec{\mathbf{A}}(\vec{\mathbf{r}}, t) = \frac{\vec{\mathbf{v}}}{c^2} V(\vec{\mathbf{r}}, t)$$

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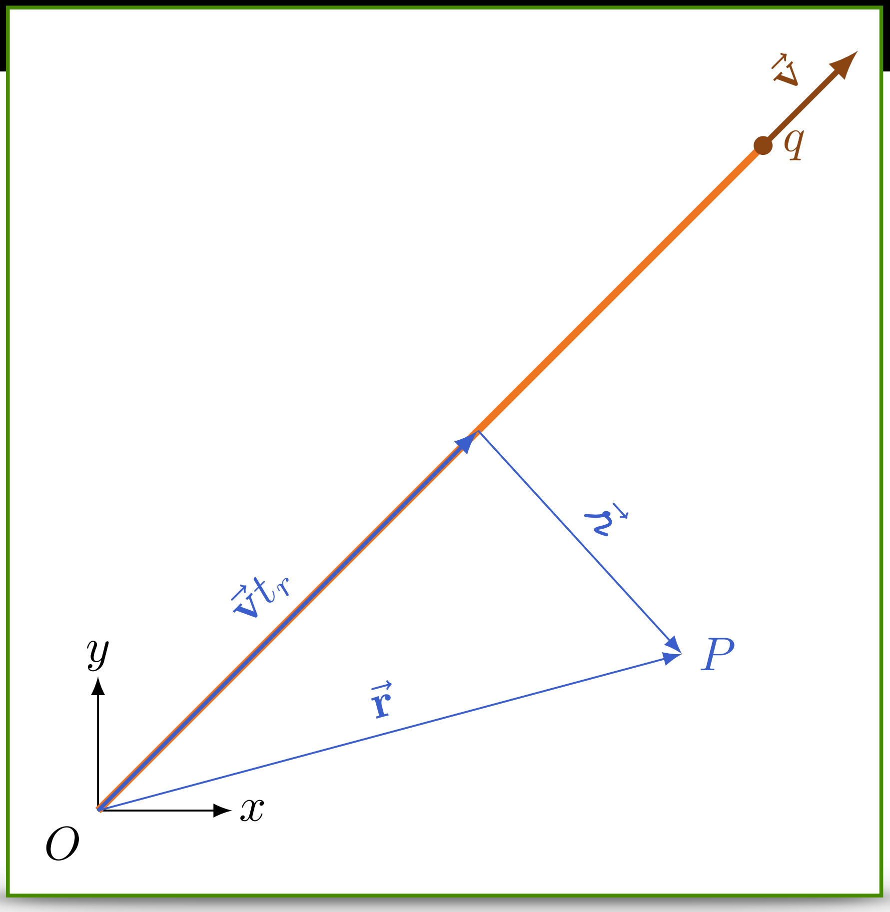
$$\vec{\mathbf{B}}(\vec{\mathbf{r}}, t) = \frac{1}{c} \hat{\mathscr{r}} \times \vec{\mathbf{E}}(\vec{\mathbf{r}}, t)$$

$\vec{\mathbf{u}} \equiv c\hat{\mathscr{r}} - \vec{\mathbf{v}}$

Pratique o que aprendeu

$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3} [(c^2 - v^2)\vec{\mathbf{u}} + \vec{\mathscr{r}} \times (\vec{\mathbf{u}} \times \vec{\mathbf{a}})]$$

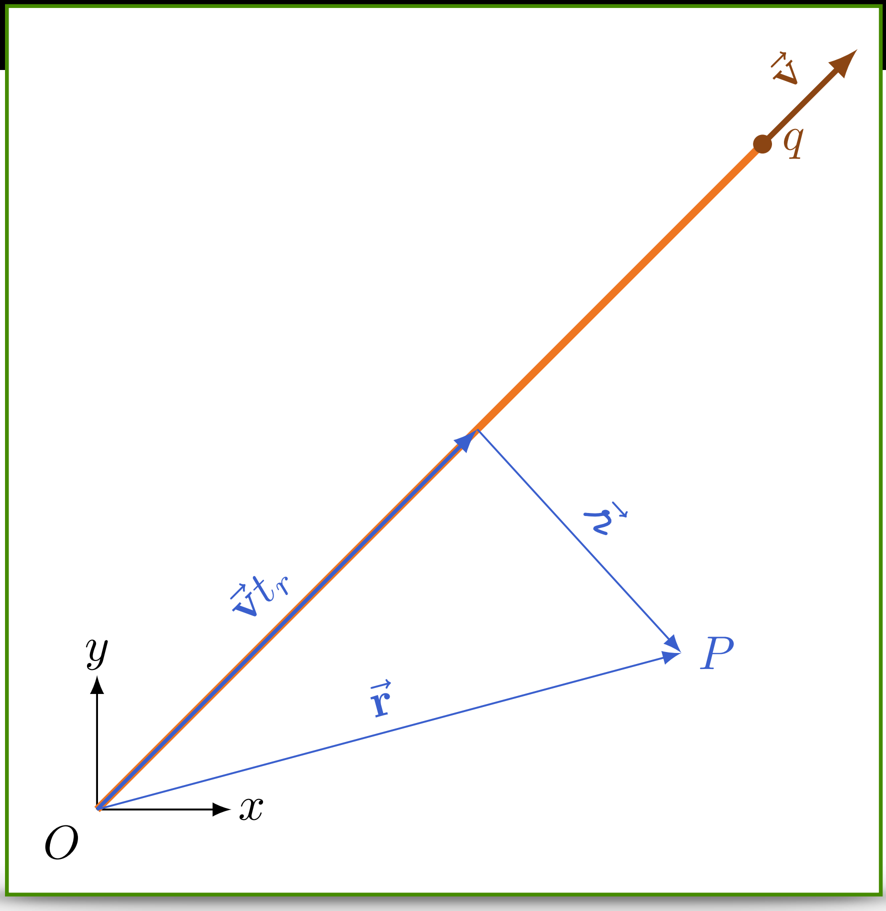


$\vec{\mathbf{u}} \equiv c\hat{\mathscr{r}} - \vec{\mathbf{v}}$

Pratique o que aprendeu

$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3} [(c^2 - v^2)\vec{\mathbf{u}} + \vec{\mathscr{r}} \times (\vec{\mathbf{u}} \times \vec{\mathbf{a}})]$$

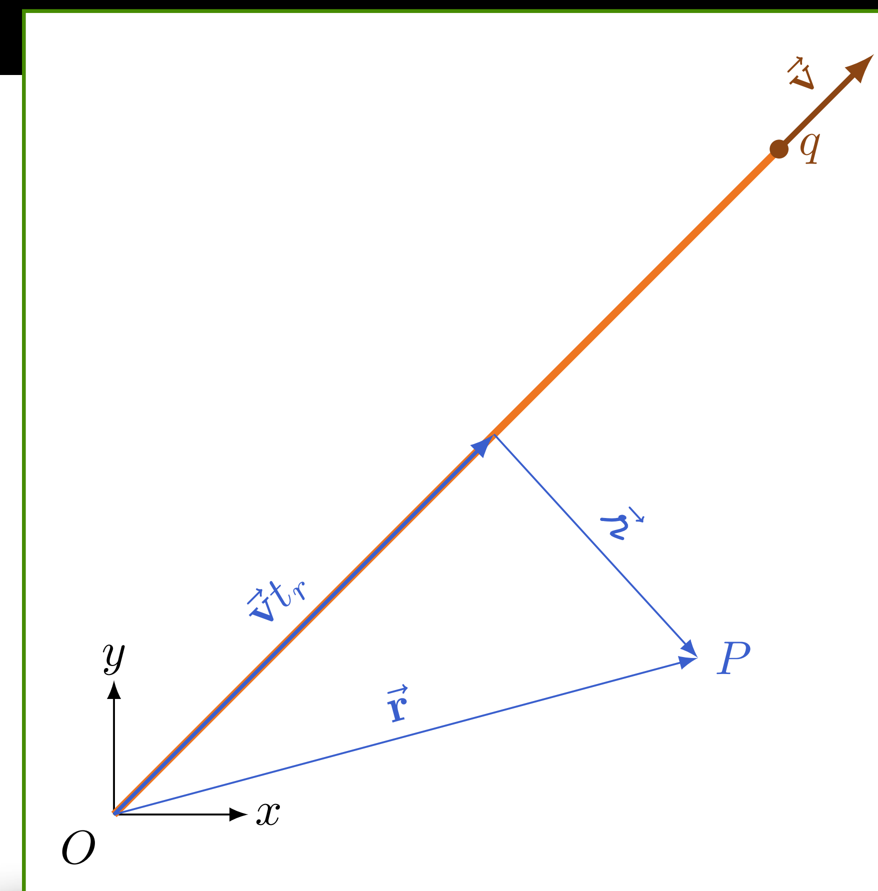
$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3} (c^2 - v^2)\vec{\mathbf{u}}$$



Pratique o que aprendeu

$$\vec{\mathbf{u}} \equiv c\hat{\mathscr{r}} - \vec{\mathbf{v}}$$

$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3} [(c^2 - v^2)\vec{\mathbf{u}} + \vec{\mathscr{r}} \times (\vec{\mathbf{u}} \times \vec{\mathbf{a}})]$$



$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3} (c^2 - v^2)\vec{\mathbf{u}}$$

$$\mathscr{r}\vec{\mathbf{u}} = c\vec{\mathscr{r}} - \mathscr{r}\vec{\mathbf{v}} = c\vec{\mathbf{r}} - c\vec{\mathbf{v}}t_r - \mathscr{r}\vec{\mathbf{v}}$$

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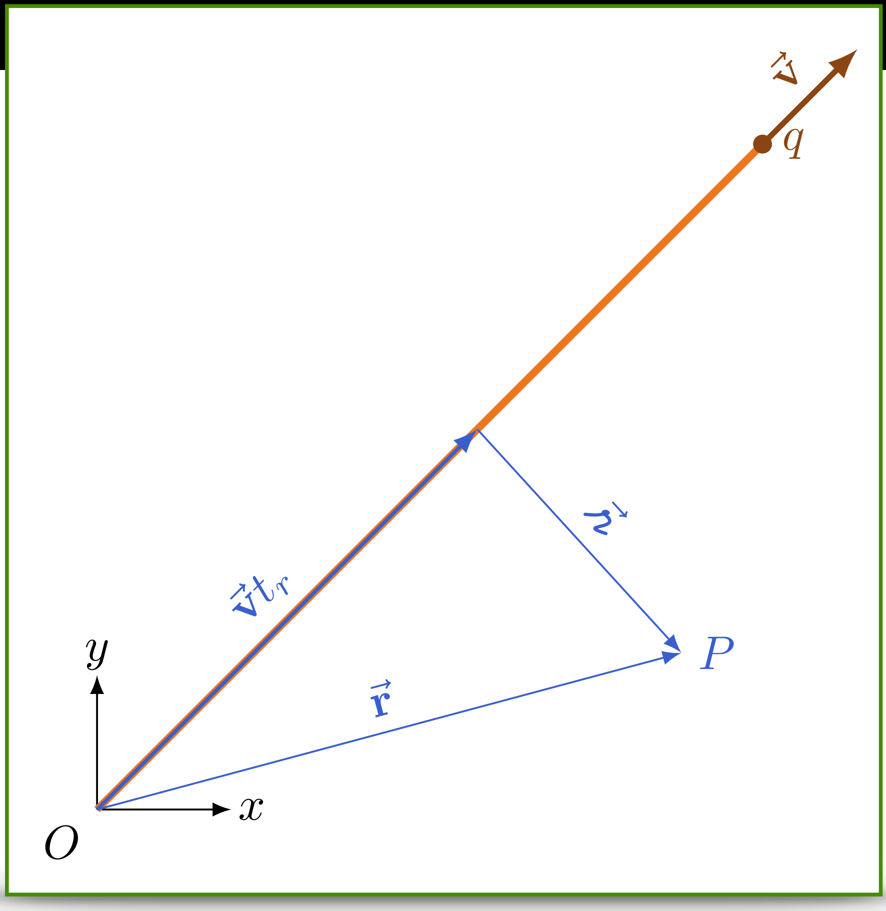

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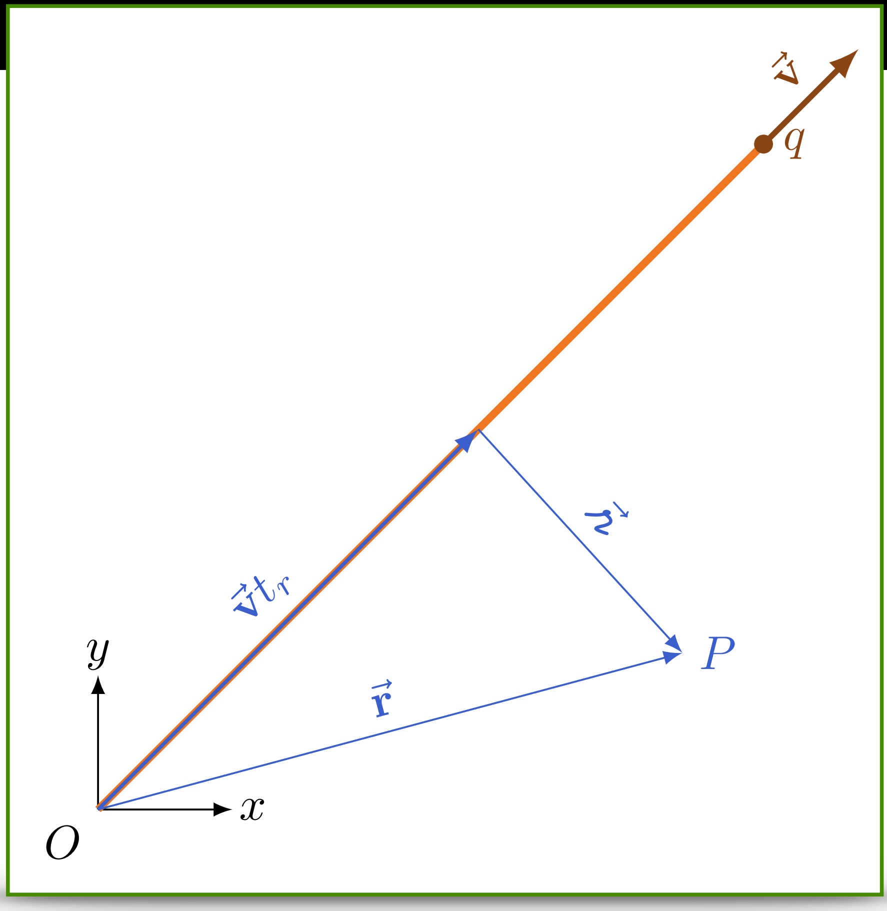
$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0}\frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3}[(c^2 - v^2)\vec{\mathbf{u}} + \vec{\mathscr{r}} \times (\vec{\mathbf{u}} \times \vec{\mathbf{a}})]$$



$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0}\frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3}(c^2 - v^2)\vec{\mathbf{u}}$$

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$$\mathscr{r}\vec{\mathbf{u}} = c\vec{\mathbf{r}} - c\vec{\mathbf{v}}t + c\vec{\mathbf{v}}\frac{\mathscr{r}}{c} - \mathscr{r}\vec{\mathbf{v}}$$

Pratique o que aprendeu

$$\vec{\mathbf{u}} \equiv c\hat{\mathscr{r}} - \vec{\mathbf{v}}$$

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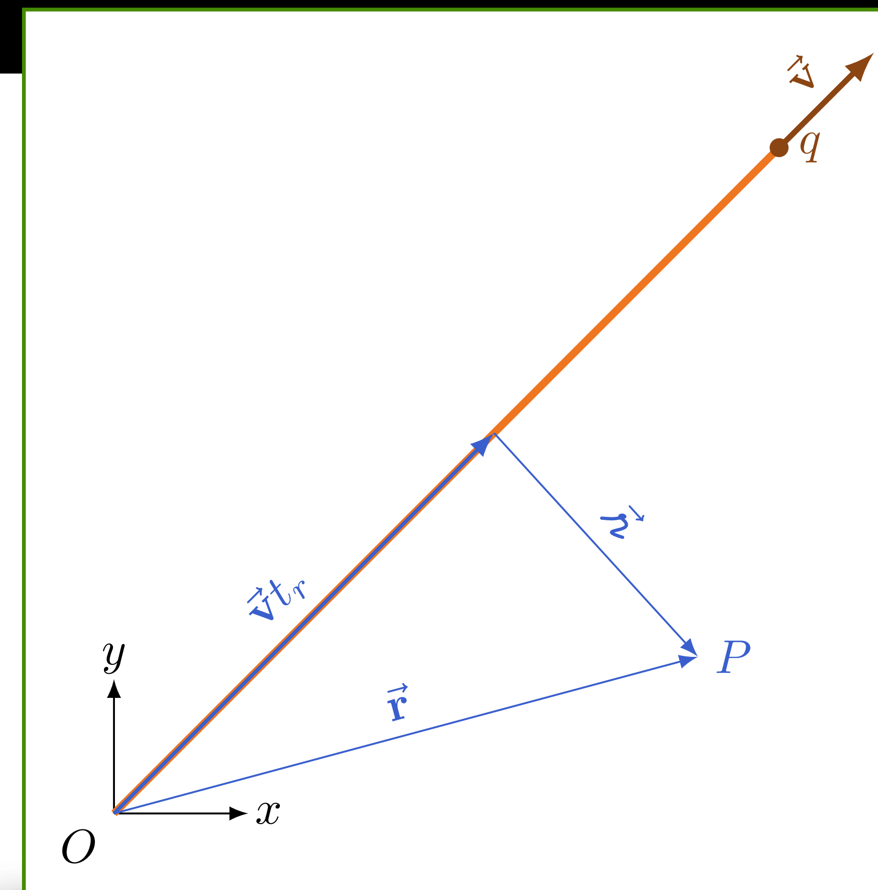

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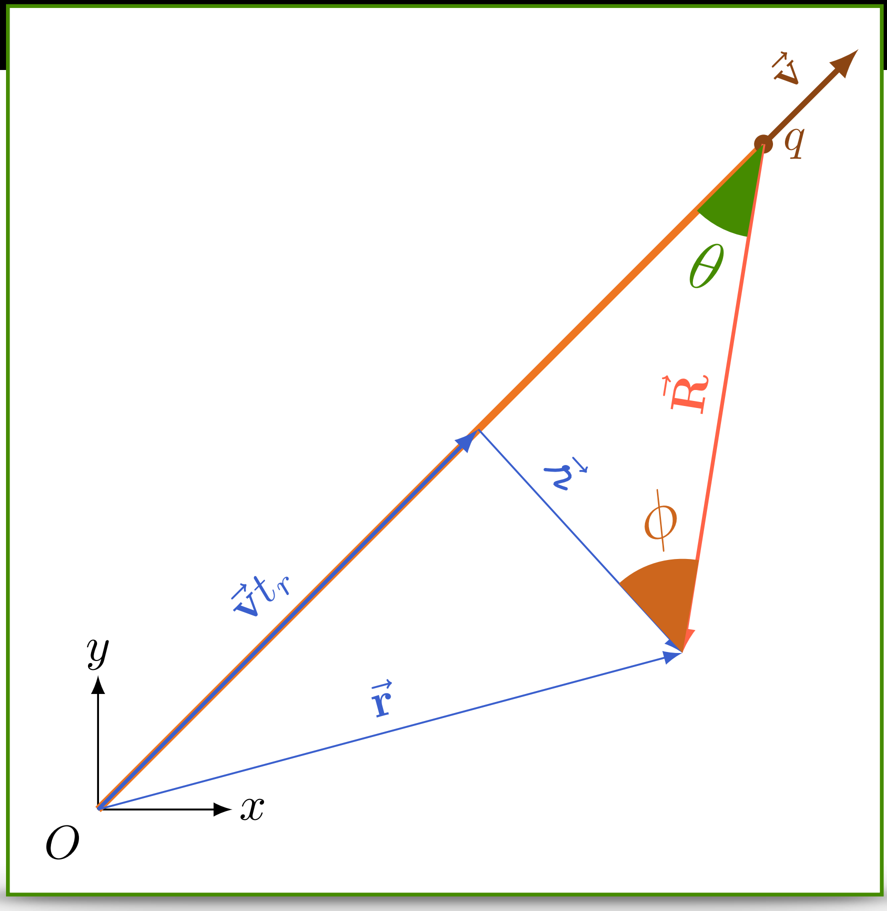
$$\mathscr{r}\vec{\mathbf{u}} = c(\vec{\mathbf{r}} - \vec{\mathbf{v}}t) \equiv c\vec{\mathbf{R}}$$

Pratique o que aprendeu

$\vec{\mathbf{u}} \equiv c\hat{\mathscr{r}} - \vec{\mathbf{v}}$

$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0}\frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3}[(c^2 - v^2)\vec{\mathbf{u}} + \vec{\mathscr{r}} \times (\vec{\mathbf{u}} \times \vec{\mathbf{a}})]$$



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Pratique o que aprendeu

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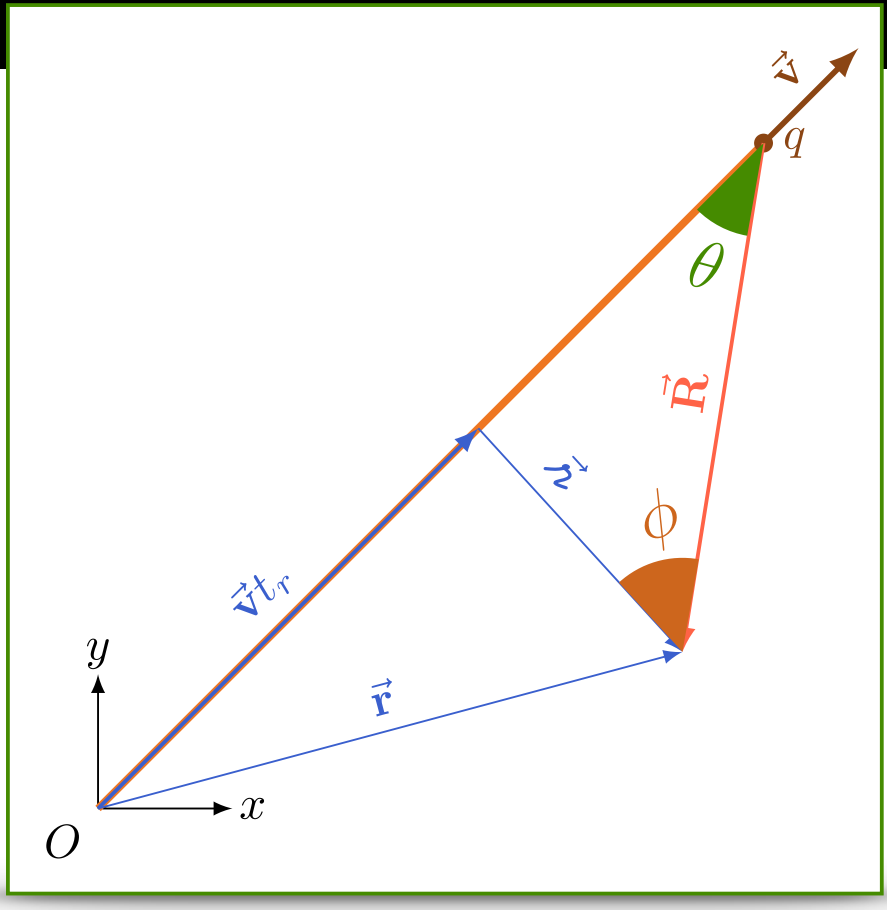
$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3} [(c^2 - v^2)\vec{\mathbf{u}} + \vec{\mathscr{r}} \times (\vec{\mathbf{u}} \times \vec{\mathbf{a}})]$$



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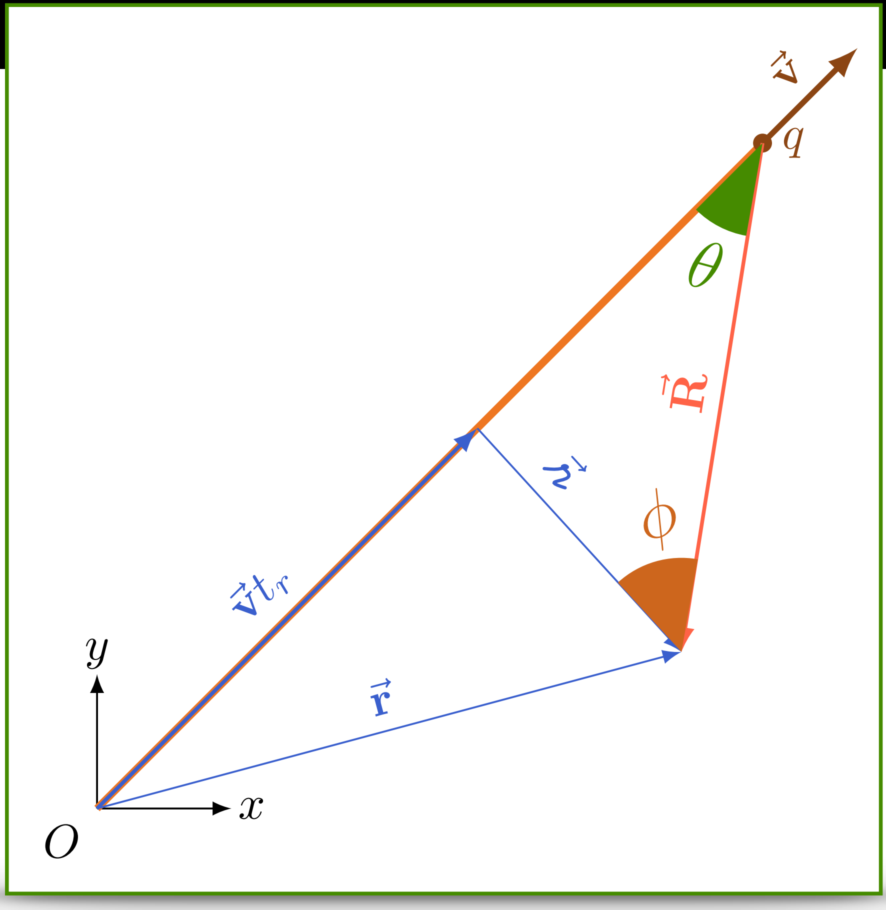
$$\mathscr{r}\vec{\mathbf{u}} = c(\vec{\mathbf{r}} - \vec{\mathbf{v}}t) \equiv c\vec{\mathbf{R}}$$

$$\frac{v(t - t_r)}{\sin\phi} = \frac{c(t - t_r)}{\sin\theta}$$



Pratique o que aprendeu

$$\vec{\mathbf{u}} \equiv c\hat{\mathscr{r}} - \vec{\mathbf{v}}$$

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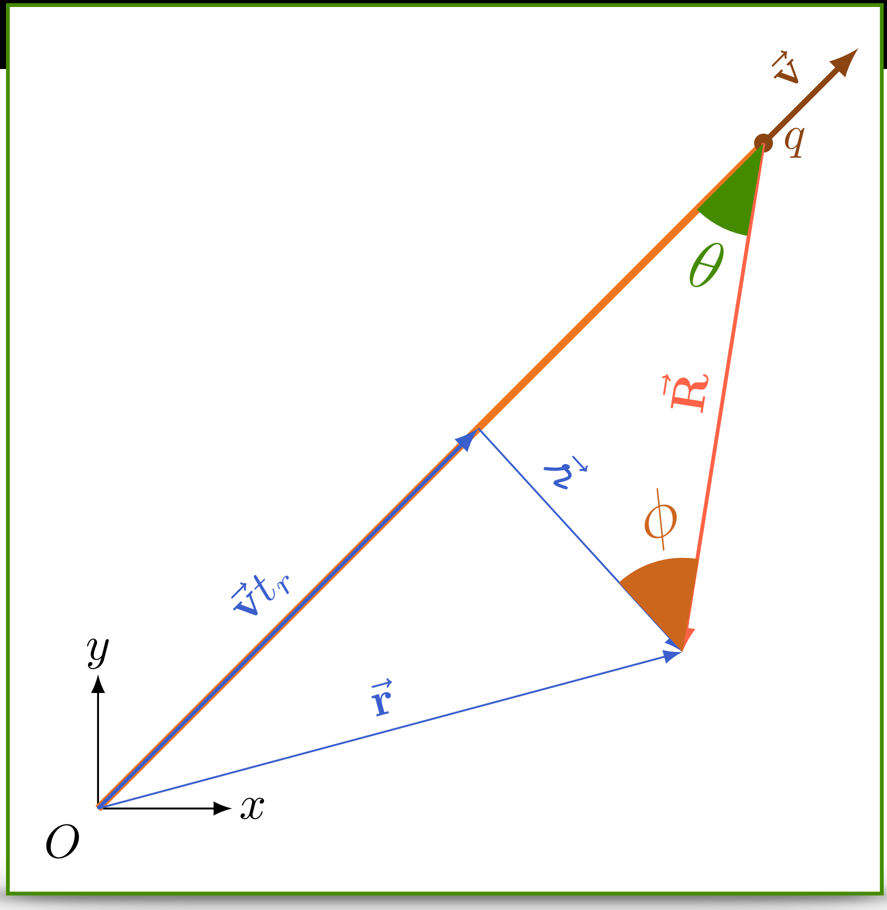


$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0}\frac{\mathscr{r}}{(\vec{\mathscr{r}}\cdot\vec{\mathbf{u}})^3}(c^2 - v^2)\vec{\mathbf{u}}$$

$$\mathscr{r}\vec{\mathbf{u}} = c(\vec{\mathbf{r}} - \vec{\mathbf{v}}t) \equiv c\vec{\mathbf{R}}$$

$$\frac{v(t - t_r)}{\sin\phi} = \frac{c(t - t_r)}{\sin\theta}$$

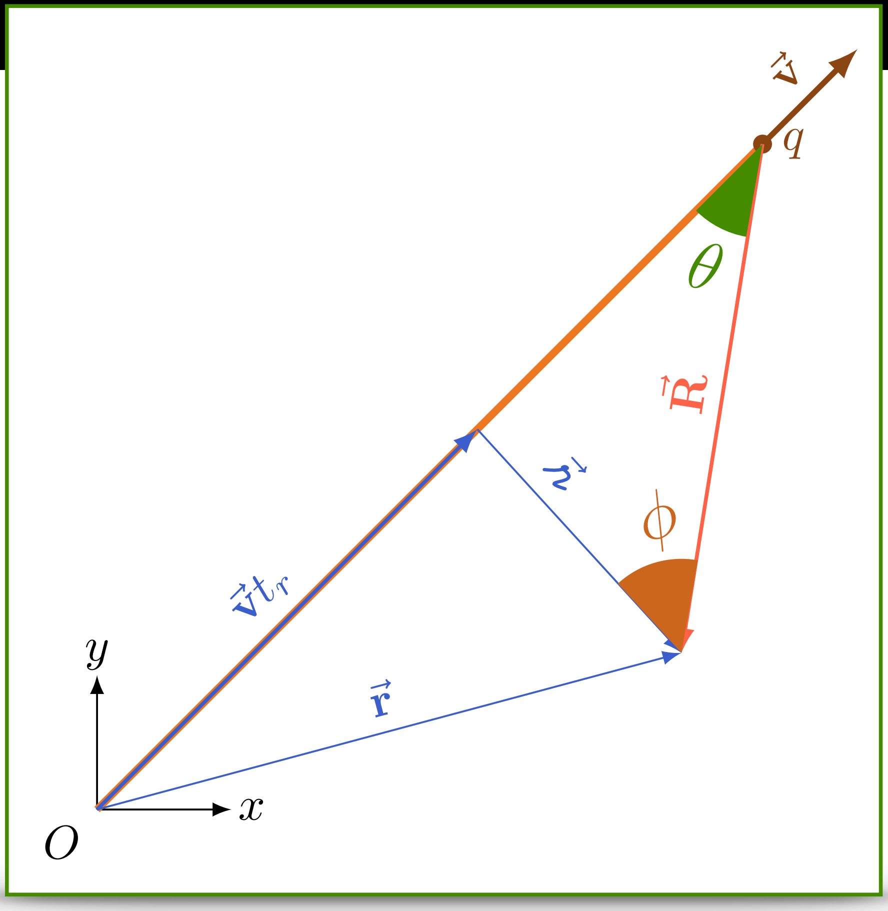
$$v\sin\theta = c\sin\phi$$

$$\cos\phi = \hat{\mathbf{R}}\cdot\hat{\mathscr{r}}$$

Pratique o que aprendeu

$$\vec{\mathbf{u}} \equiv c\hat{\mathscr{r}} - \vec{\mathbf{v}}$$

$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0}\frac{\mathscr{r}}{(\vec{\mathscr{r}}\cdot\vec{\mathbf{u}})^3}[(c^2 - v^2)\vec{\mathbf{u}} + \vec{\mathscr{r}} \times (\vec{\mathbf{u}} \times \vec{\mathbf{a}})]$$



$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0}\frac{\mathscr{r}}{(\vec{\mathscr{r}}\cdot\vec{\mathbf{u}})^3}(c^2 - v^2)\vec{\mathbf{u}}$$

$$\mathscr{r}\vec{\mathbf{u}} = c(\vec{\mathbf{r}} - \vec{\mathbf{v}}t) \equiv c\vec{\mathbf{R}}$$

$$\frac{v(t - t_r)}{\sin\phi} = \frac{c(t - t_r)}{\sin\theta}$$

$$v\sin\theta = c\sin\phi$$

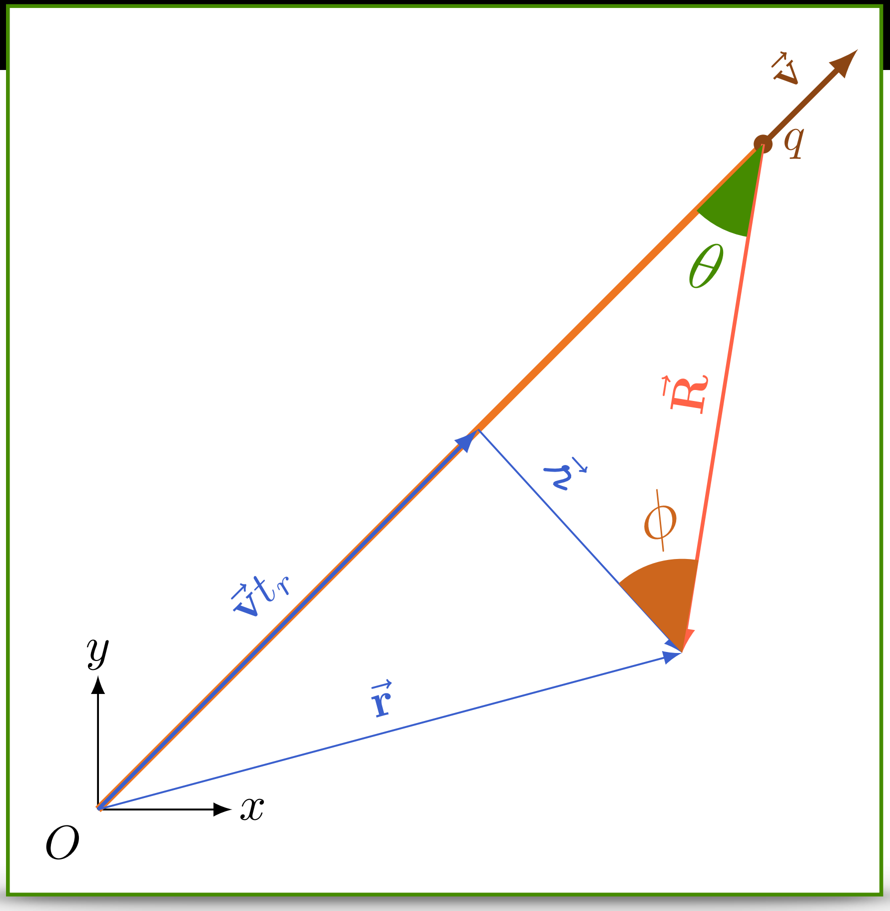
$$\cos\phi = \hat{\mathbf{u}}\cdot\hat{\mathscr{r}}$$

$$\hat{\mathbf{u}}\cdot\hat{\mathscr{r}} = \sqrt{1 - \sin^2\phi}$$

Pratique o que aprendeu

$$\vec{\mathbf{u}} \equiv c\hat{\mathbf{\mathscr{r}}} - \vec{\mathbf{v}}$$

$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3} [(c^2 - v^2)\vec{\mathbf{u}} + \vec{\mathscr{r}} \times (\vec{\mathbf{u}} \times \vec{\mathbf{a}})]$$



$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3} (c^2 - v^2)\vec{\mathbf{u}}$$

$$\mathscr{r}\vec{\mathbf{u}} = c(\vec{\mathbf{r}} - \vec{\mathbf{v}}t) \equiv c\vec{\mathbf{R}}$$

$$\frac{v(t - t_r)}{\sin\phi} = \frac{c(t - t_r)}{\sin\theta}$$

$$v\sin\theta = c\sin\phi$$

$$\cos\phi = \hat{\mathbf{u}} \cdot \hat{\mathscr{r}}$$

$$\hat{\mathbf{u}} \cdot \hat{\mathscr{r}} = \sqrt{1 - \sin^2\phi}$$

$$\hat{\mathbf{u}} \cdot \hat{\mathscr{r}} = \sqrt{1 - \left(\frac{v}{c}\right)^2 \sin^2\theta}$$

Pratique o que aprendeu

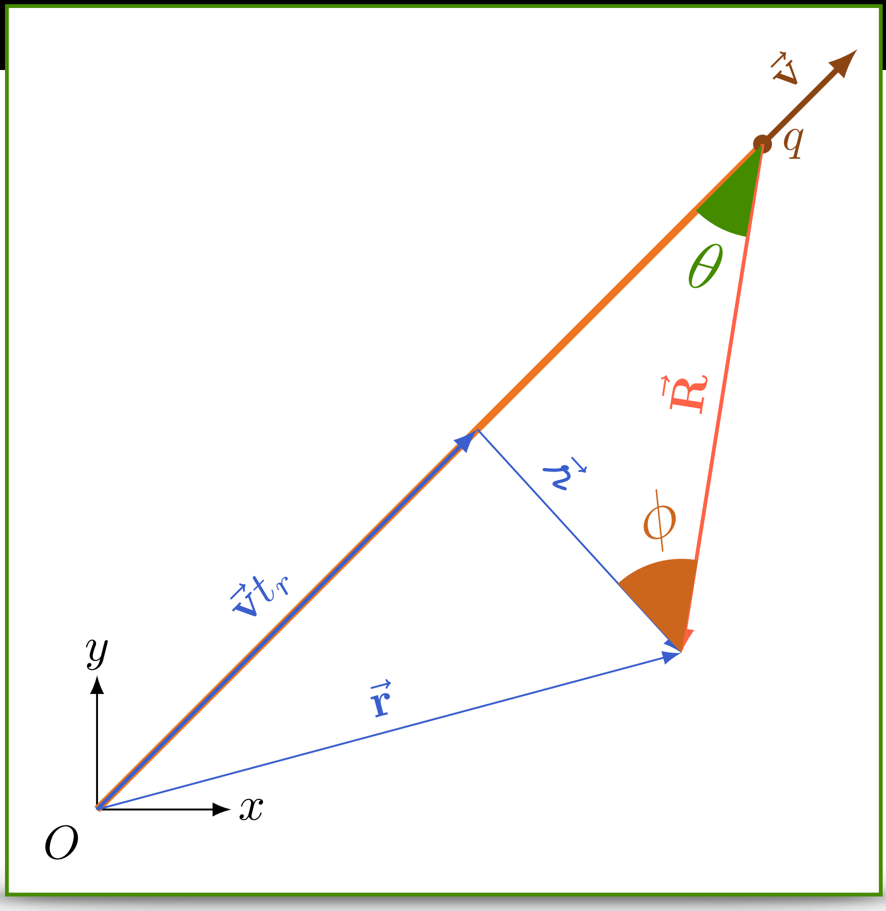
$\vec{\mathbf{u}} \equiv c\hat{\boldsymbol{\mathscr{r}}} - \vec{\mathbf{v}}$

$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\boldsymbol{\mathscr{r}}} \cdot \vec{\mathbf{u}})^3} [(c^2 - v^2)\vec{\mathbf{u}} + \vec{\boldsymbol{\mathscr{r}}} \times (\vec{\mathbf{u}} \times \vec{\mathbf{a}})]$$

$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\boldsymbol{\mathscr{r}}} \cdot \vec{\mathbf{u}})^3} (c^2 - v^2)\vec{\mathbf{u}}$$

$$\mathscr{r}\vec{\mathbf{u}} = c(\vec{\mathbf{r}} - \vec{\mathbf{v}}t) \equiv c\vec{\mathbf{R}}$$

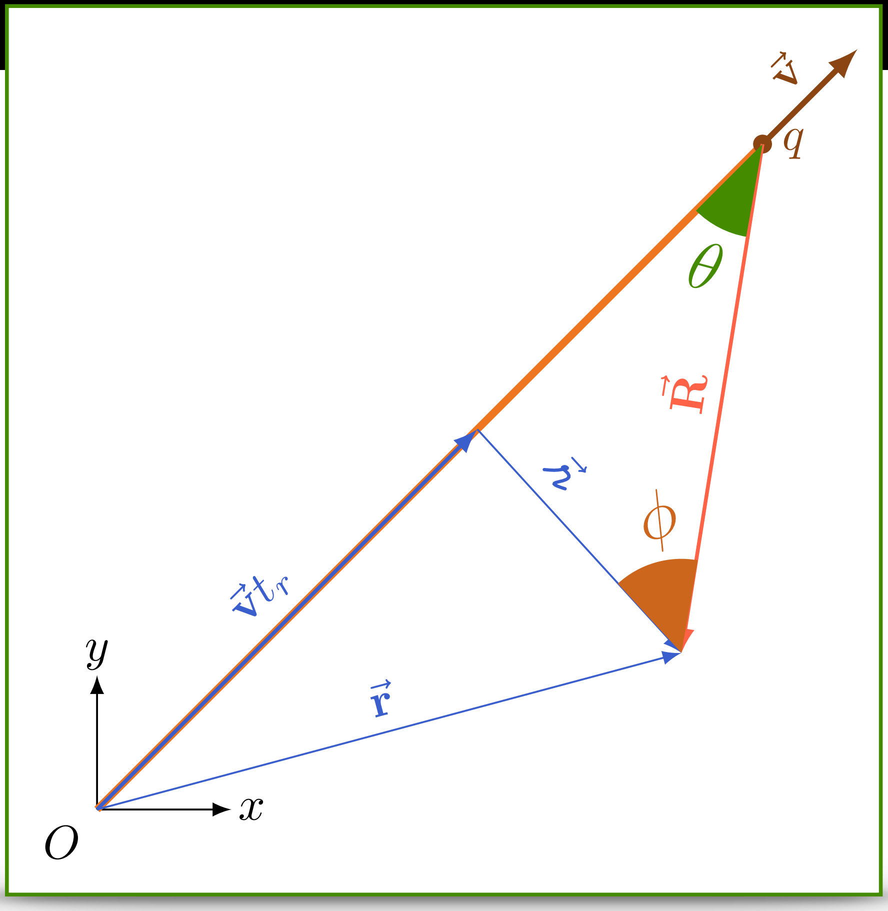
$$\hat{\mathbf{u}} \cdot \hat{\boldsymbol{\mathscr{r}}} = \sqrt{1 - \left(\frac{v}{c}\right)^2 \sin^2\theta}$$



Pratique o que aprendeu

$$\vec{\mathbf{u}} \equiv c\hat{\mathscr{r}} - \vec{\mathbf{v}}$$

$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3} [(c^2 - v^2)\vec{\mathbf{u}} + \vec{\mathscr{r}} \times (\vec{\mathbf{u}} \times \vec{\mathbf{a}})]$$



$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\vec{\mathscr{r}} \cdot \vec{\mathbf{u}})^3} (c^2 - v^2)\vec{\mathbf{u}}$$

$$\mathscr{r}\vec{\mathbf{u}} = c(\vec{\mathbf{r}} - \vec{\mathbf{v}}t) \equiv c\vec{\mathbf{R}}$$

$$\hat{\mathbf{u}} \cdot \hat{\mathscr{r}} = \sqrt{1 - \left(\frac{v}{c}\right)^2 \sin^2\theta}$$

$$\vec{\mathbf{E}}(\vec{\mathbf{r}}, t) = \frac{q}{4\pi\epsilon_0} \frac{\mathscr{r}}{(\mathscr{r}u)^3 \left(1 - \left(\frac{v}{c}\right)^2 \sin^2\theta\right)^{3/2}} (c^2 - v^2)\vec{\mathbf{u}}$$

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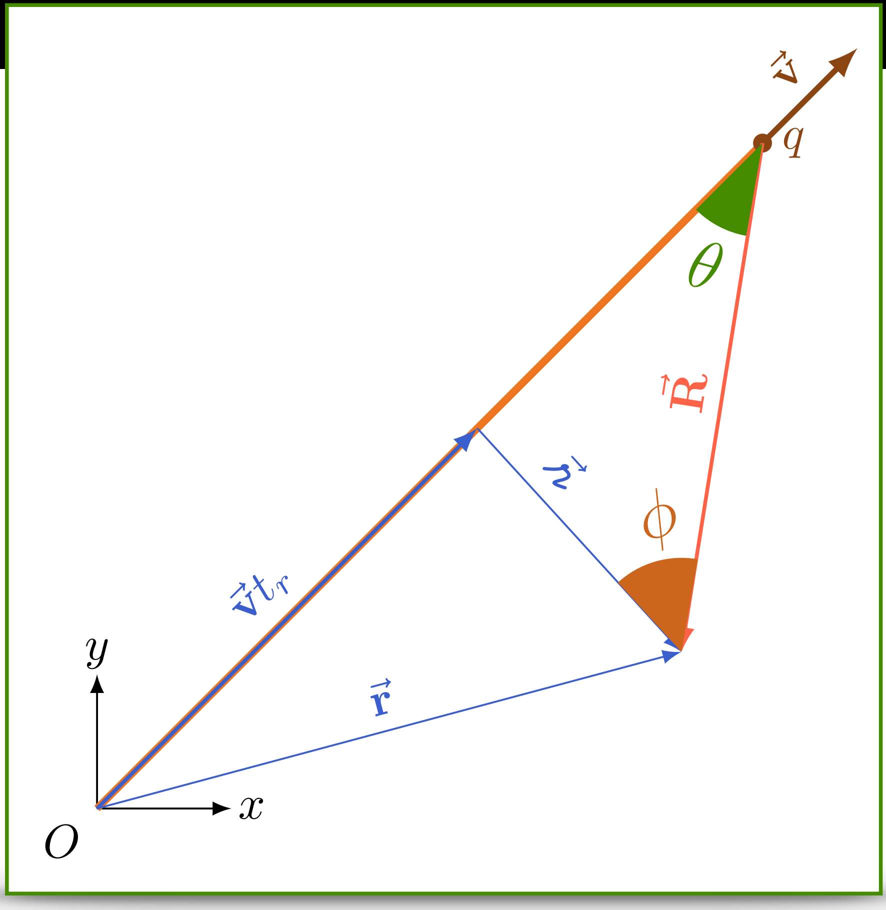

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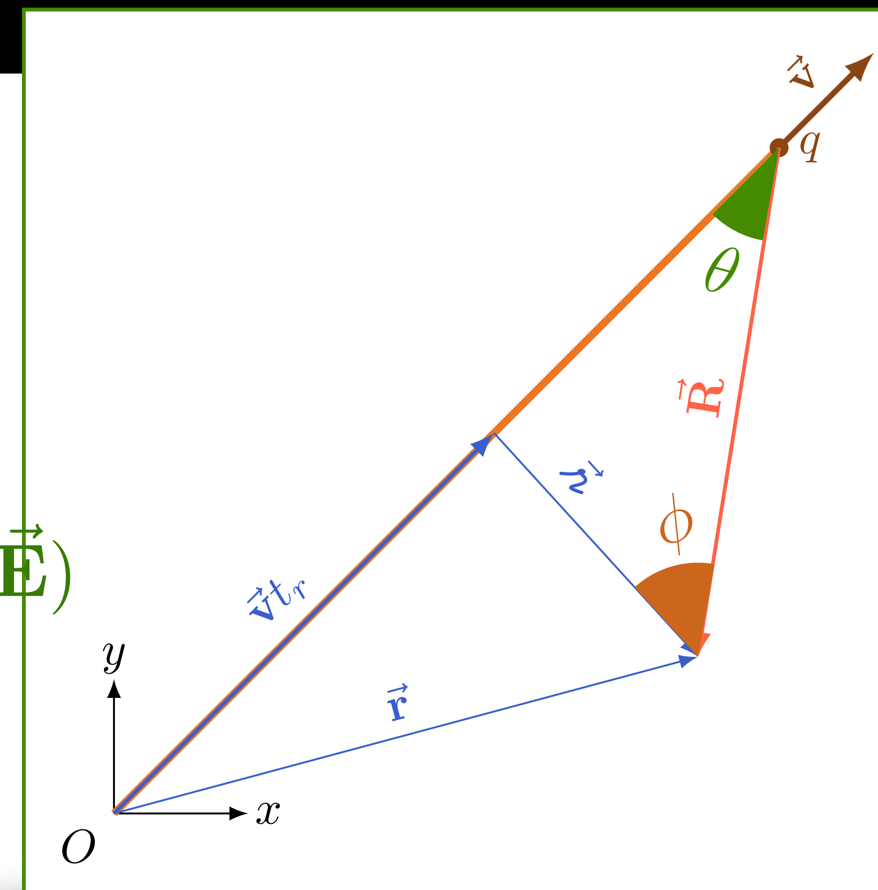

$$\vec{\mathbf{E}}(\vec{\mathbf{r}},t) = \frac{q}{4\pi\epsilon_0}\frac{\mathscr{r}}{(\vec{\mathscr{r}}\cdot\vec{\mathbf{u}})^3}(c^2-v^2)\vec{\mathbf{u}}$$

$$\vec{\mathbf{B}}(\vec{\mathbf{r}},t) = \frac{1}{c}(\hat{\mathscr{r}}\times\vec{\mathbf{E}})$$

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$$\vec{\mathbf{E}}(\vec{\mathbf{r}},t) = \frac{q}{4\pi\epsilon_0}\frac{\mathscr{r}}{(\mathscr{r}u)^3\left(1-\left(\frac{v}{c}\right)^2\sin^2\theta\right)^{3/2}}(c^2-v^2)\vec{\mathbf{u}}$$

$$\vec{\mathbf{E}}(\vec{\mathbf{r}},t) = \frac{q}{4\pi\epsilon_0}\frac{1-\left(\frac{v}{c}\right)^2}{\left(1-\left(\frac{v}{c}\right)^2\sin^2\theta\right)^{3/2}}\frac{\hat{\mathbf{R}}}{R^2}$$

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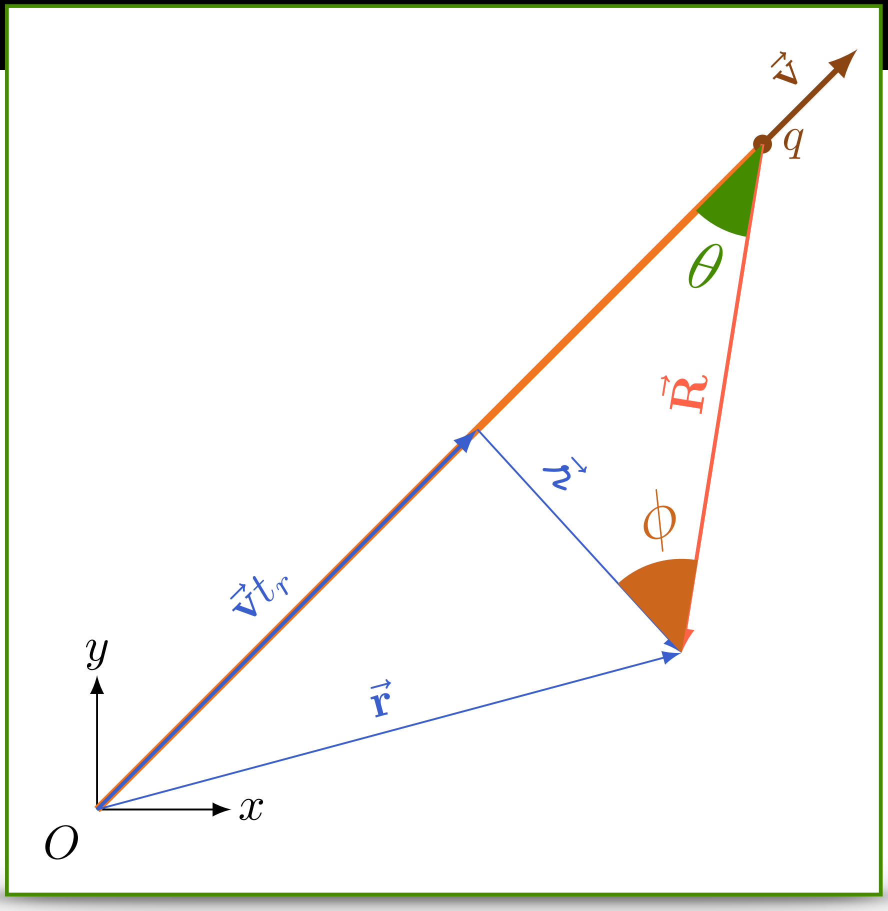

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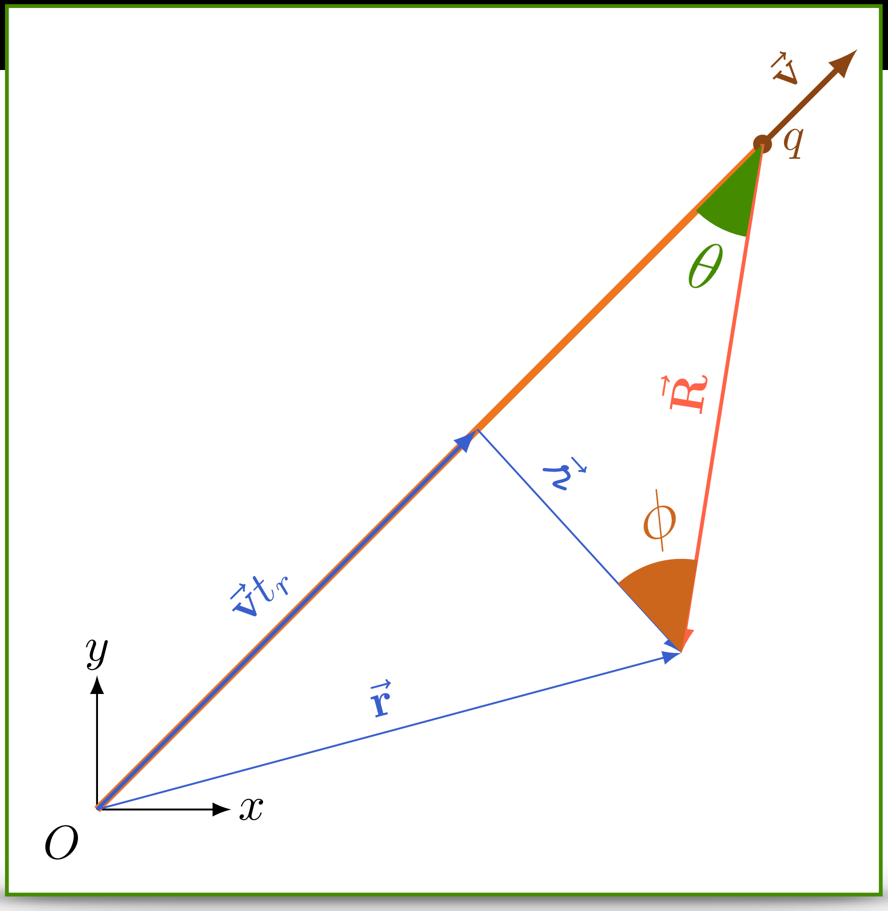

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