Eletromagnetismo

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

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

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

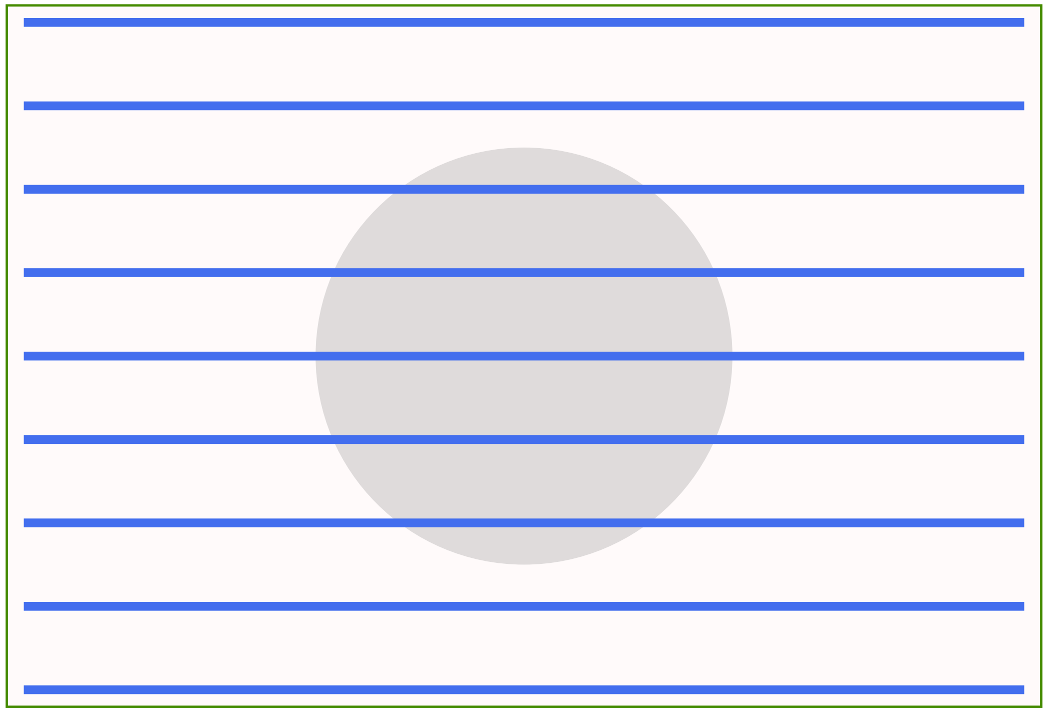
$$\vec{\nabla} \times \vec{H} = \vec{j} + \epsilon_0 \frac{\partial \vec{D}}{\partial t}$$

7 de julho de 2021

Magnetismo em materiais

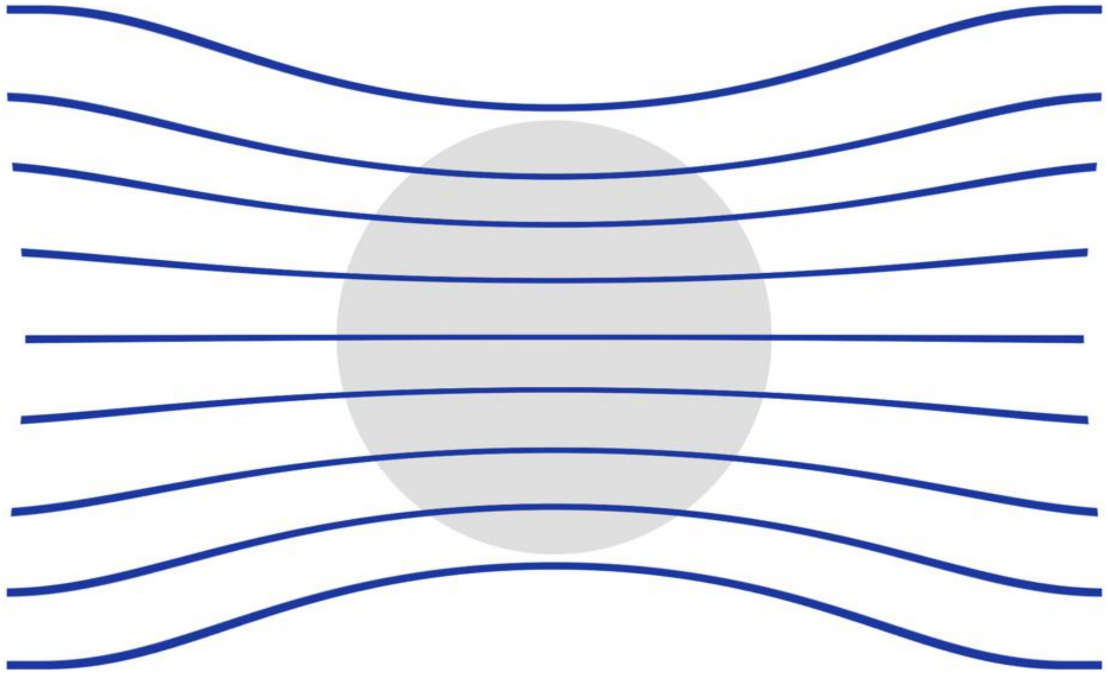
Magnetismo em materiais

- Paramagnéticos
- Diamagnéticos
- Ferromagnéticos
- Antiferromagnéticos



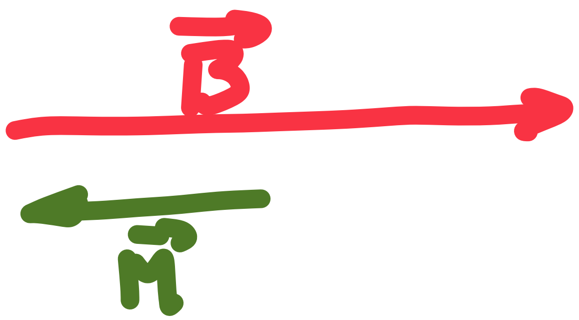
Magnetismo em materiais

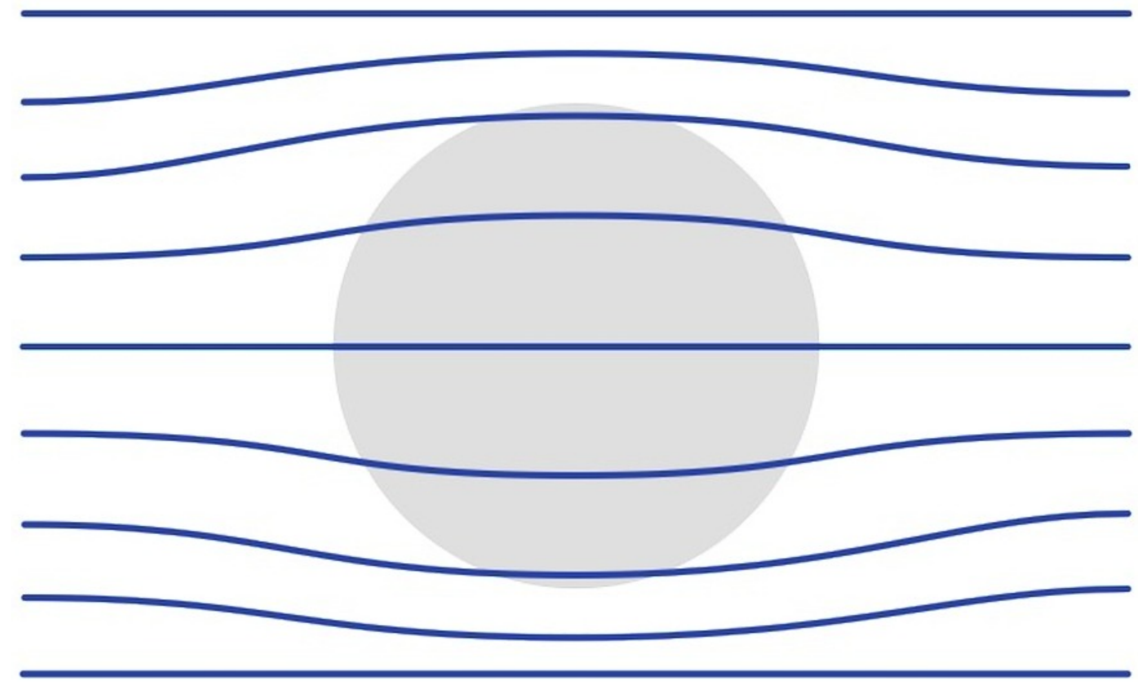
- Paramagnéticos



Magnetismo em materiais

- Diamagnéticos



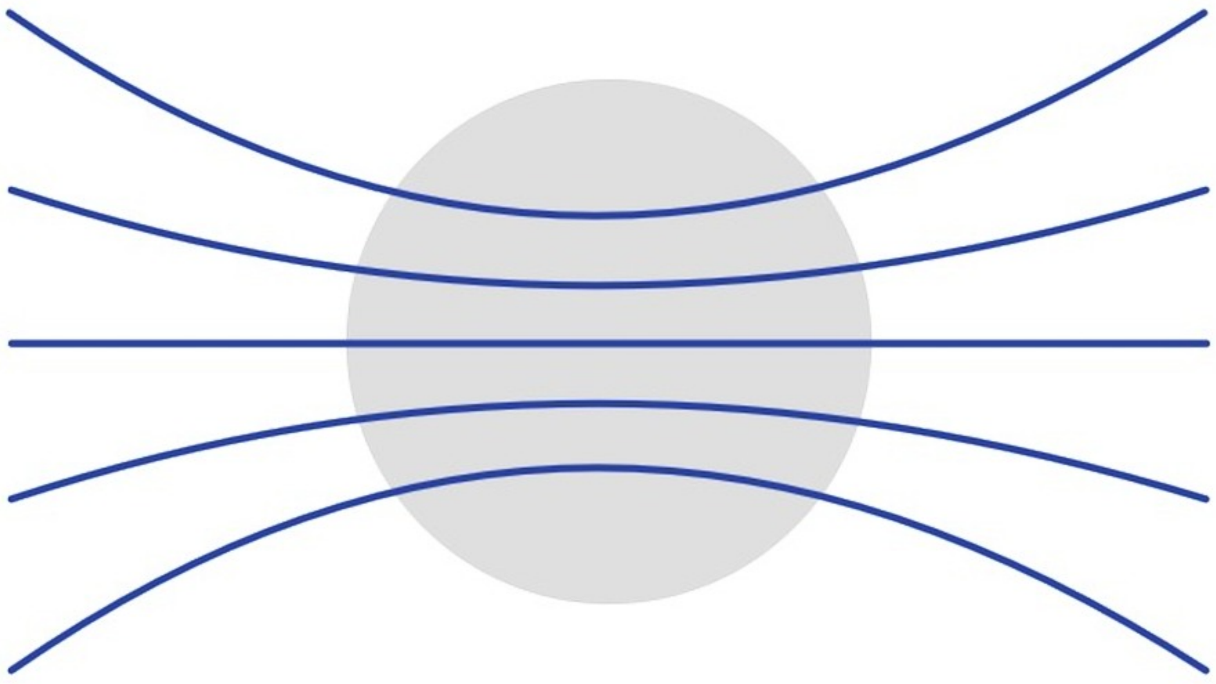


Magnetismo em materiais

- Ferromagnéticos

$\vec{M}$

$\vec{B} = 0$

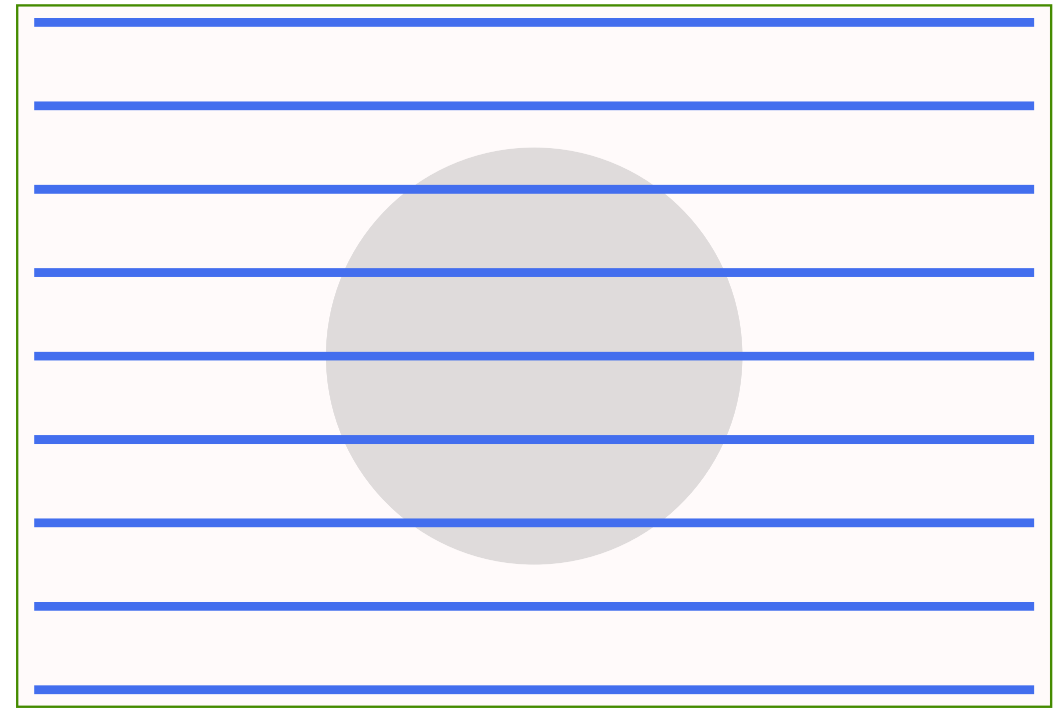


Magnetismo em materiais

- Antiferromagnéticos

$\vec{B}$

$\vec{M} = 0$

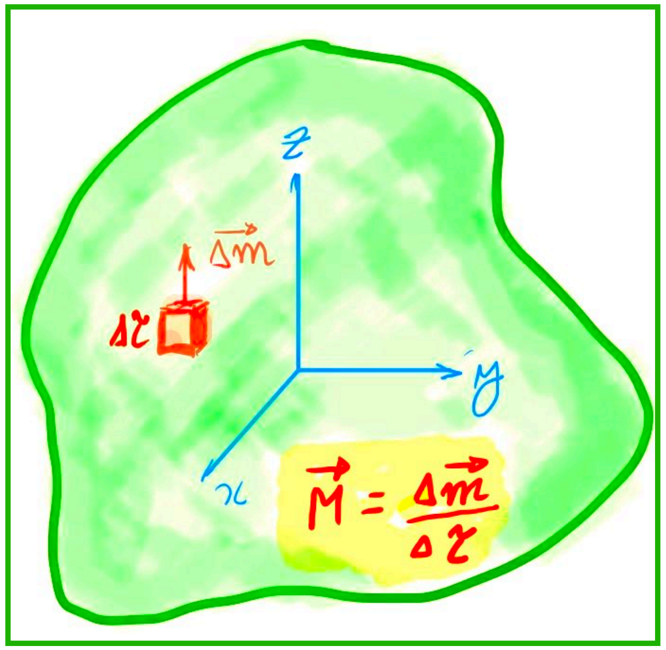


Magnetização

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi} \frac{\vec{m} \times \hat{r}}{r^2}$$

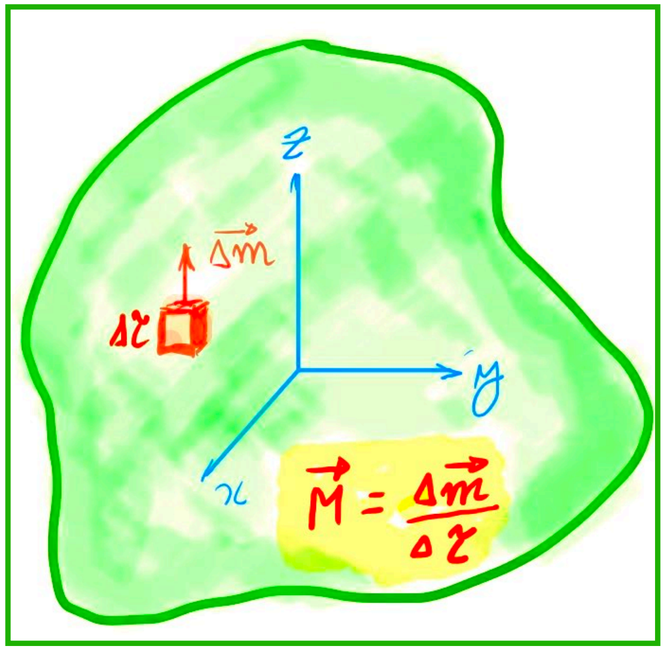
$$\vec{M} = \frac{\Delta \vec{m}}{\Delta \tau}$$

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi} \int \frac{\vec{M}(\vec{r'}) \times \hat{\mathscr{r}}}{\mathscr{r}^2} \, d\tau'$$



Magnetização

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi}\int \frac{1}{\mathscr{r}}\vec{\nabla}\times\vec{M}(\vec{r'})\,\mathrm{d}\tau' + \frac{\mu_0}{4\pi}\int\frac{1}{\mathscr{r}}\vec{M}(\vec{r'})\times\hat{n}\,\mathrm{d}a'$$



DENSIDADES DE CORRENTE

$$\vec{\nabla}\times\vec{M}(\vec{r'}) \equiv \vec{J}_b$$

VOLUMÉTRICA

$$\vec{M}(\vec{r'})\times\hat{n} \equiv \vec{K}_b$$

SUPERFICIAL

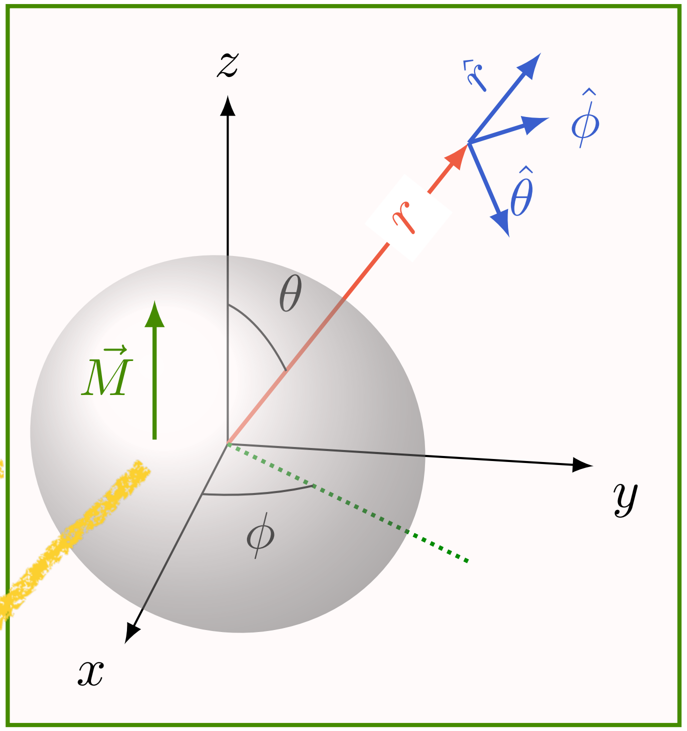
$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi}\int \frac{\vec{J}_b(\vec{r'})}{\mathscr{r}}\,\mathrm{d}\tau' + \frac{\mu_0}{4\pi}\int\frac{\vec{K}_b(\vec{r'})}{\mathscr{r}}\,\mathrm{d}a'$$

Pratique o que aprendeu

$$\vec{\nabla} \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$

QUAIS SÃO AS DENSIDADES DE CORRENTE?

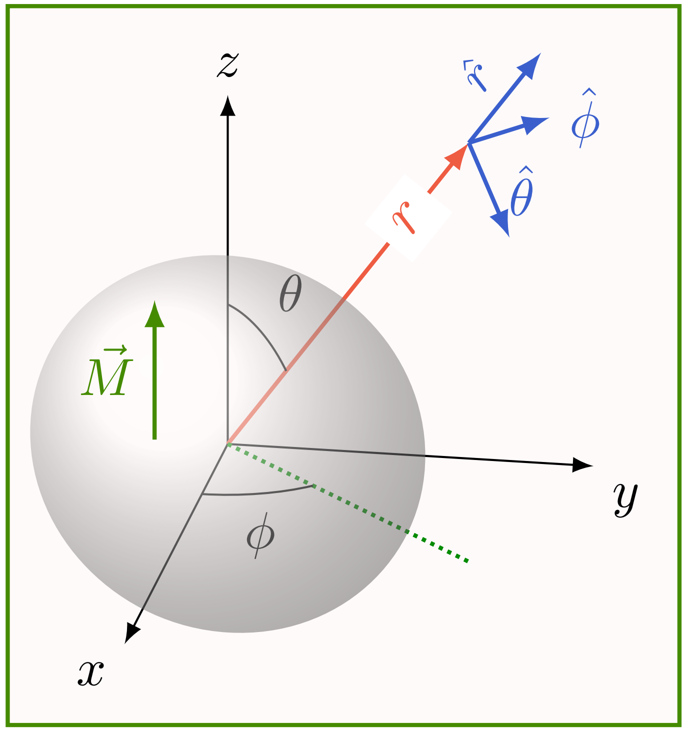


UNIFORME

Pratique o que aprendeu

$$\vec{\nabla}' \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$



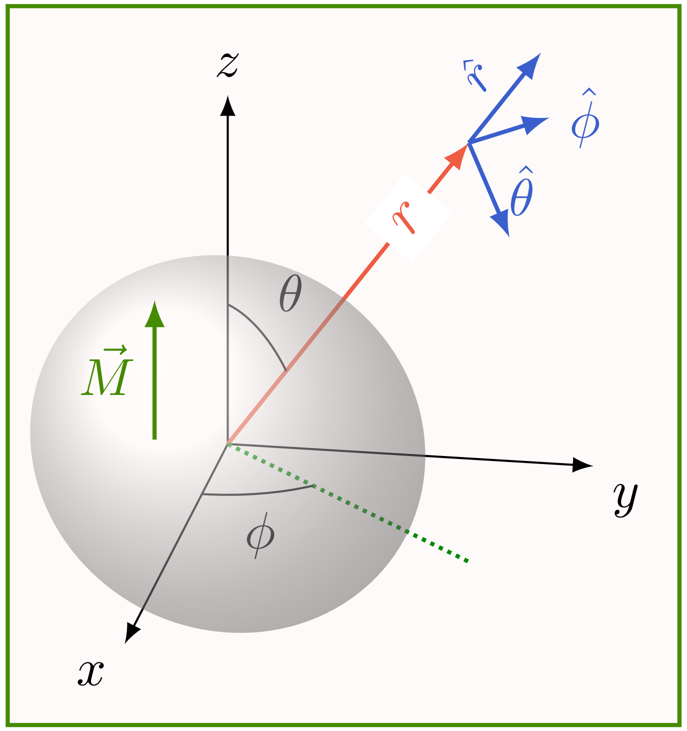
$$\vec{\nabla} \times \vec{M} = 0 \quad \Rightarrow \quad \vec{J}_b = 0$$

$$\vec{K}_b = ?$$

Pratique o que aprendeu

$$\vec{\nabla}' \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$



$$\vec{\nabla} \times \vec{M} = 0 \quad \Rightarrow \quad \vec{J}_b = 0$$

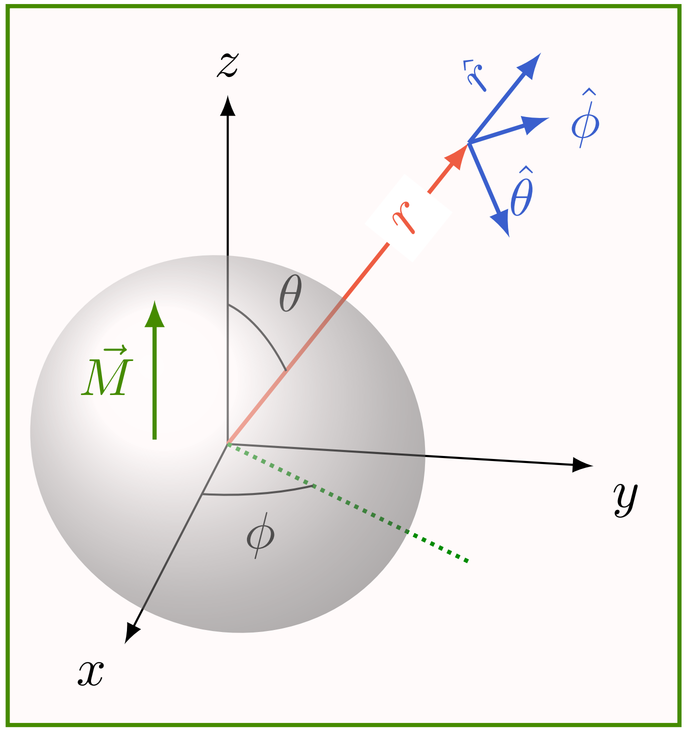
$$\vec{M} \times \hat{n} = M\hat{z} \times \hat{r}$$

EXPRESSAR EM COORDENADAS ESFÉRICAS

Pratique o que aprendeu

$$\vec{\nabla}' \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$



$$\vec{\nabla} \times \vec{M} = 0 \quad \Rightarrow \quad \vec{J}_b = 0$$

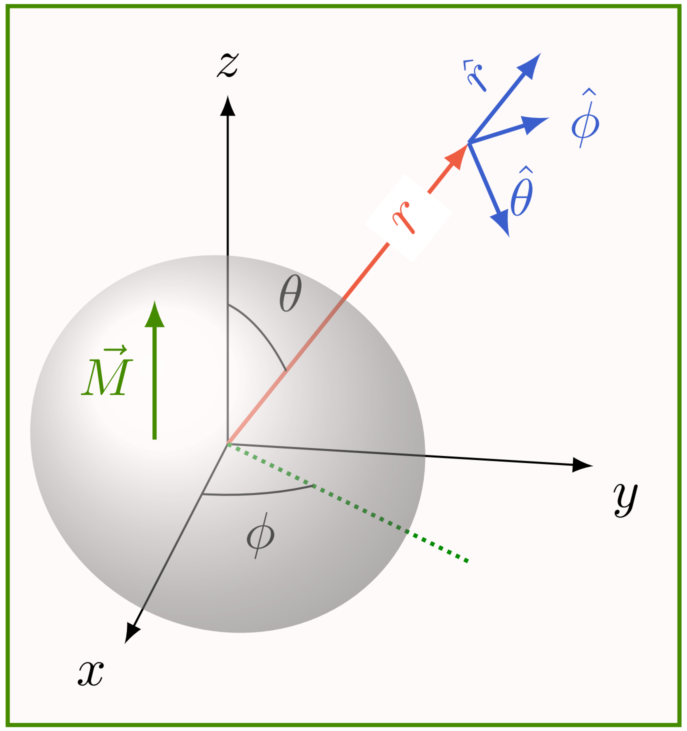
$$\vec{M} \times \hat{n} = M\hat{z} \times \hat{r}$$

$$\hat{z} = \underbrace{\cos\theta}_{\hat{z}\cdot\hat{r}}\,\hat{r} \underbrace{-\sin\theta}_{\hat{z}\cdot\hat{\theta}}\,\hat{\theta}$$

Pratique o que aprendeu

$$\vec{\nabla}' \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

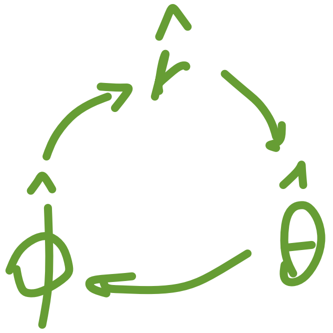
$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$



$$\vec{\nabla} \times \vec{M} = 0 \quad \Rightarrow \quad \vec{J}_b = 0$$

$$\vec{M} \times \hat{n} = M \hat{z} \times \hat{r}$$

$$\hat{z} = \cos\theta \, \hat{r} - \sin\theta \, \hat{\theta}$$

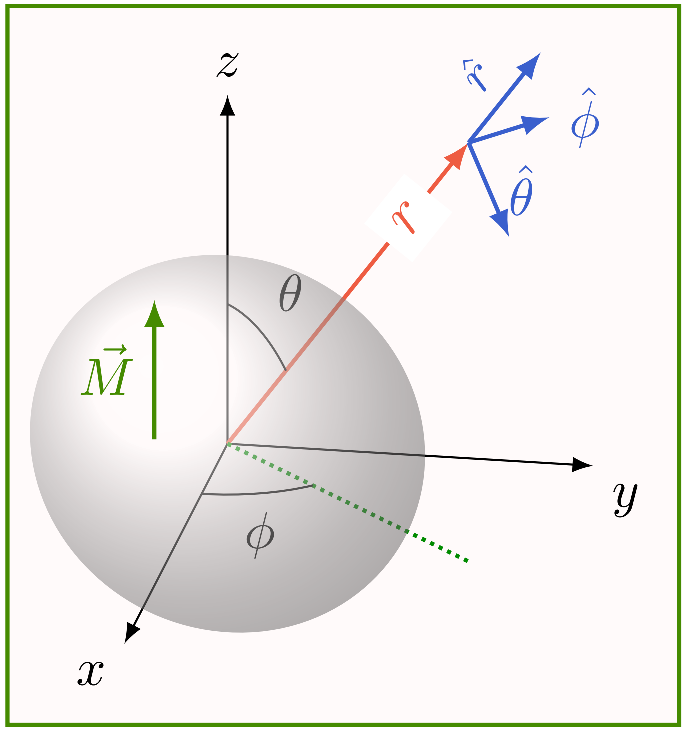


$$\vec{M} \times \hat{n} = M \sin\theta \, \hat{\phi}$$

Pratique o que aprendeu

$$\vec{\nabla}' \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$



$$\vec{\nabla} \times \vec{M} = 0 \quad \Rightarrow \quad \vec{J}_b = 0$$

$$\vec{M} \times \hat{n} = M \hat{z} \times \hat{r}$$

$$\hat{z} = \cos\theta\, \hat{r} - \sin\theta\, \hat{\theta}$$

$$\vec{M} \times \hat{n} = M \sin\theta\, \hat{\phi}$$

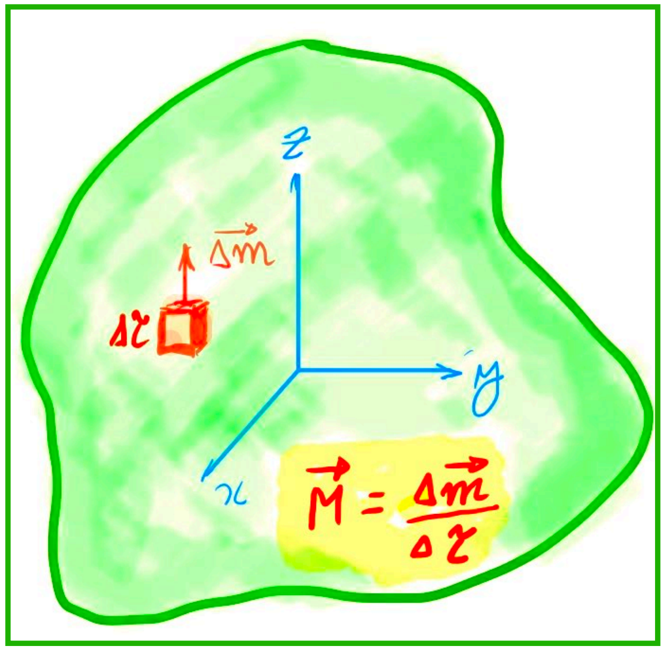
$$\vec{K}_b = M \sin\theta\, \hat{\phi}$$

→ COMO SE FOSSE ESFERA COM SUPERFÍCIE CARREGADA EM ROTAÇÃO

Magnetização

$$\vec{\nabla} \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$



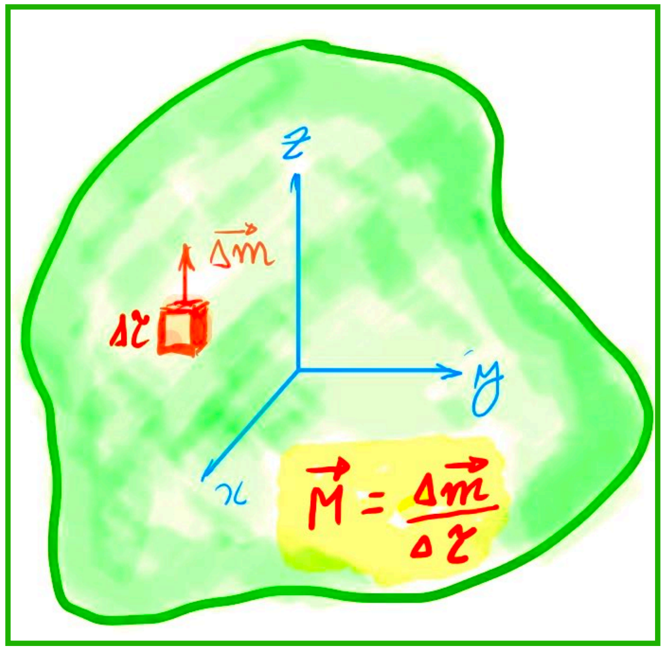
$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi}\int \frac{\vec{J}(\vec{r'})}{\mathscr{r}}\,\mathrm{d}\tau' + \frac{\mu_0}{4\pi}\int \frac{\vec{K}(\vec{r'})}{\mathscr{r}}\,\mathrm{d}a'$$

EM GERAL, ALÉM DAS CORRENTES DE MAGNETIZAÇÃO, HÁ CORRENTES DE ELÉTRONS LIVRES

Magnetização

$$\vec{\nabla} \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$



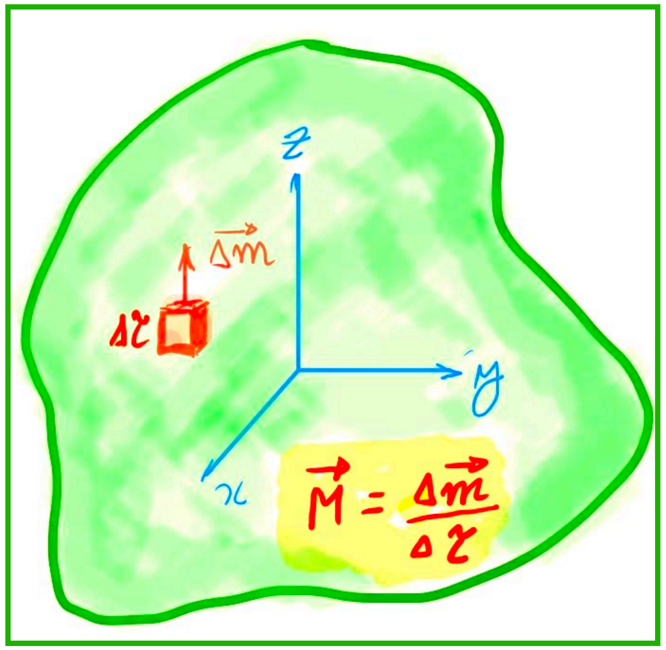
$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi}\int \frac{\vec{J}(\vec{r'})}{\mathscr{r}}\,\mathrm{d}\tau' + \frac{\mu_0}{4\pi}\int \frac{\vec{K}(\vec{r'})}{\mathscr{r}}\,\mathrm{d}a'$$

$$\vec{J} = \vec{J}_f + \vec{J}_b \qquad \vec{K} = \vec{K}_f + \vec{K}_b$$

Magnetização

$$\vec{\nabla} \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$



$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi}\int \frac{\vec{J}(\vec{r'})}{\mathscr{r}}\,\mathrm{d}\tau' + \frac{\mu_0}{4\pi}\int \frac{\vec{K}(\vec{r'})}{\mathscr{r}}\,\mathrm{d}a'$$

$$\vec{J} = \vec{J}_f + \vec{J}_b \qquad \vec{K} = \vec{K}_f + \vec{K}_b$$

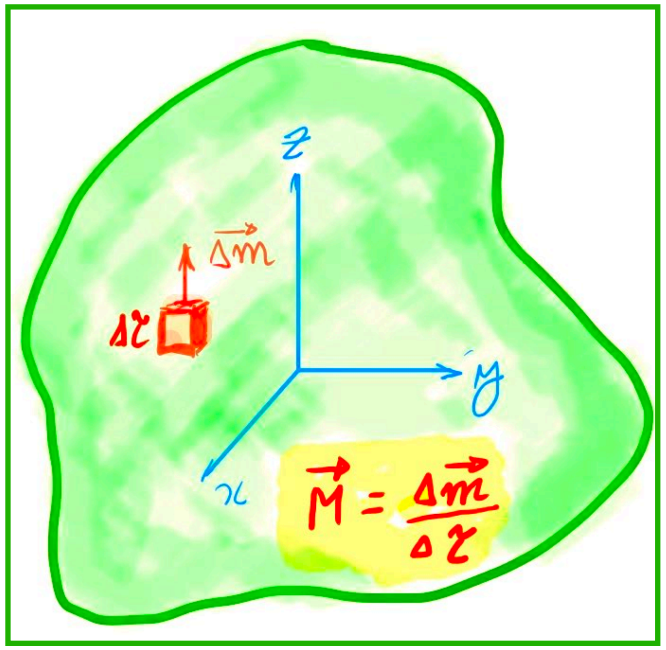
$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$$

→ LEI DE AMPÈRE

Magnetização

$$\vec{\nabla} \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$



$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi} \int \frac{\vec{J}(\vec{r'})}{\mathscr{r}} \, d\tau' + \frac{\mu_0}{4\pi} \int \frac{\vec{K}(\vec{r'})}{\mathscr{r}} \, da'$$

$$\vec{J} = \vec{J}_f + \vec{J}_b \qquad \vec{K} = \vec{K}_f + \vec{K}_b$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$$

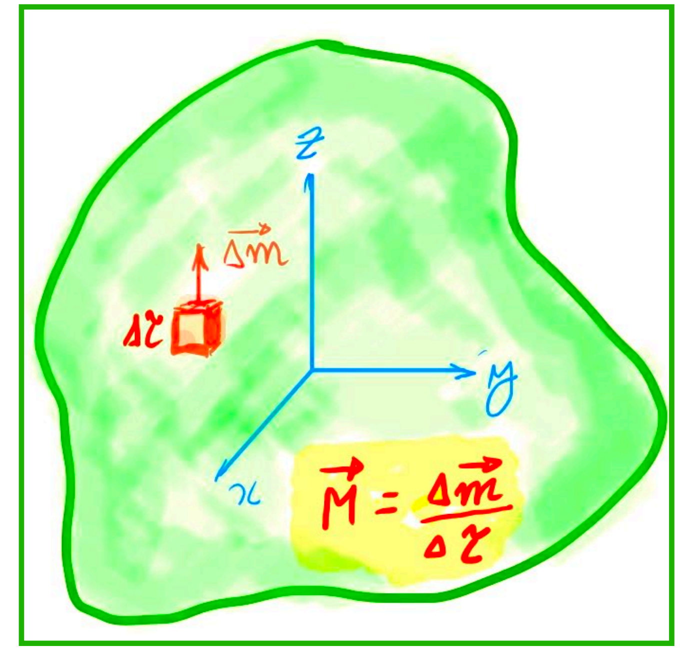
$$\vec{\nabla} \times \vec{B} = \mu_0 (\vec{J}_f + \vec{J}_b)$$

(INCLUI CORRENTES SUPERFICIAS, SE HOUVER)

Magnetização

$$\vec{\nabla} \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$



$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi} \int \frac{\vec{J}(\vec{r'})}{\mathscr{r}} \, d\tau' + \frac{\mu_0}{4\pi} \int \frac{\vec{K}(\vec{r'})}{\mathscr{r}} \, da'$$

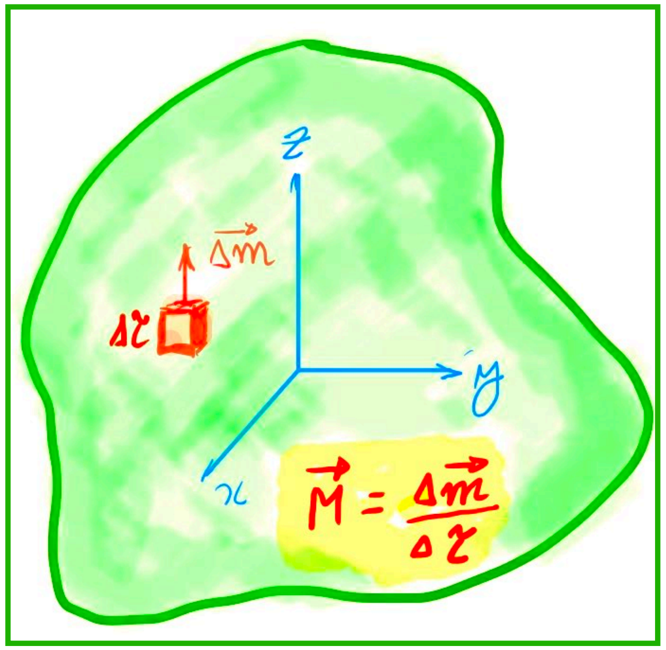
$$\vec{J} = \vec{J}_f + \vec{J}_b \qquad \vec{K} = \vec{K}_f + \vec{K}_b$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 (\vec{J}_f + \vec{J}_b)$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}_f + \mu_0 \vec{\nabla} \times \vec{M}$$

Magnetização



$$\vec{\nabla} \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi} \int \frac{\vec{J}(\vec{r'})}{\mathscr{r}} \, \mathrm{d}\tau' + \frac{\mu_0}{4\pi} \int \frac{\vec{K}(\vec{r'})}{\mathscr{r}} \, \mathrm{d}a'$$

$$\vec{J} = \vec{J}_f + \vec{J}_b$$

$$\vec{K} = \vec{K}_f + \vec{K}_b$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 (\vec{J}_f + \vec{J}_b)$$

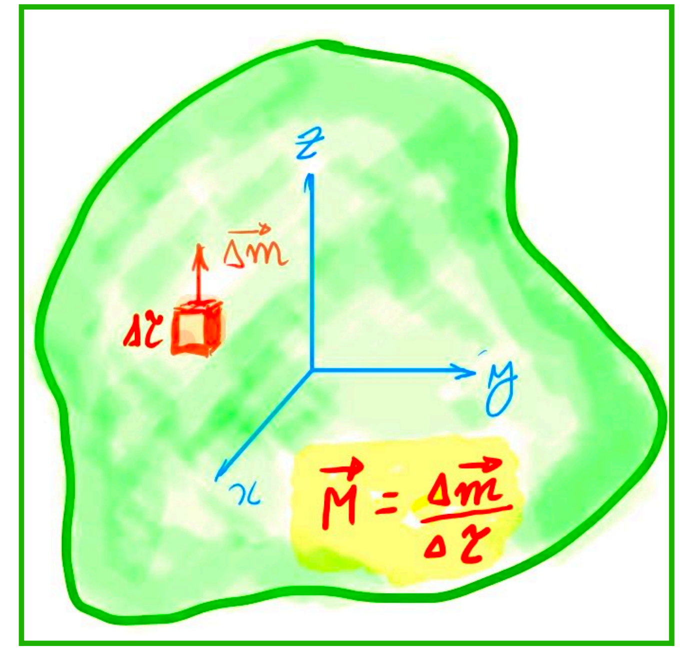
$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}_f + \mu_0 \vec{\nabla} \times \vec{M}$$

$$\vec{\nabla} \times \vec{B} - \mu_0 \vec{\nabla} \times \vec{M} = \mu_0 \vec{J}_f$$

Magnetização

$$\vec{\nabla} \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$



$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi} \int \frac{\vec{J}(\vec{r'})}{\mathscr{r}}\, \mathrm{d}\tau' + \frac{\mu_0}{4\pi} \int \frac{\vec{K}(\vec{r'})}{\mathscr{r}}\, \mathrm{d}a'$$

$$\vec{J} = \vec{J}_f + \vec{J}_b \qquad \vec{K} = \vec{K}_f + \vec{K}_b$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 (\vec{J}_f + \vec{J}_b)$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}_f + \mu_0 \vec{\nabla} \times \vec{M}$$

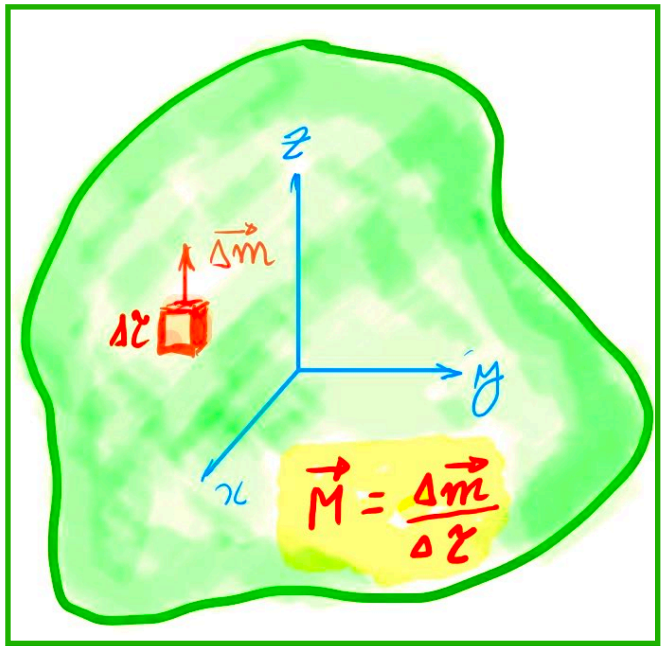
CAMPO SENSÍVEL A $\vec{J}_f$, APENAS

$$\vec{\nabla} \times \vec{B} - \mu_0 \vec{\nabla} \times \vec{M} = \mu_0 \vec{J}_f \quad \Rightarrow \quad \vec{\nabla} \times \underbrace{\left(\vec{B} - \mu_0 \vec{M}\right)}_{} = \mu_0 \vec{J}_f$$

Magnetização

$$\vec{\nabla} \times \vec{M}(\vec{r'}) \equiv \vec{J}_b$$

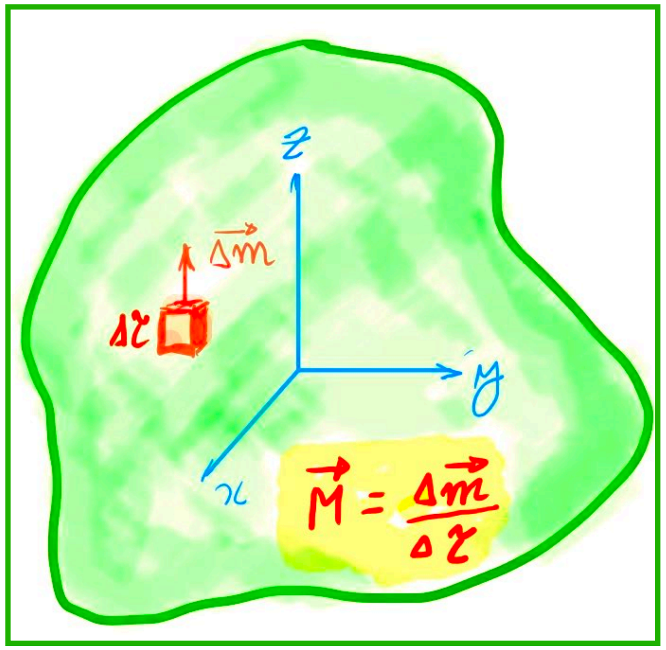
$$\vec{M}(\vec{r'}) \times \hat{n} \equiv \vec{K}_b$$



$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$$

$$\vec{\nabla} \times \vec{B} - \mu_0 \vec{\nabla} \times \vec{M} = \mu_0 \vec{J}_f \quad \Rightarrow \quad \vec{\nabla} \times \Big(\underbrace{\vec{B} - \mu_0 \vec{M}}_{\mu_0 \vec{H}} \Big) = \mu_0 \vec{J}_f$$

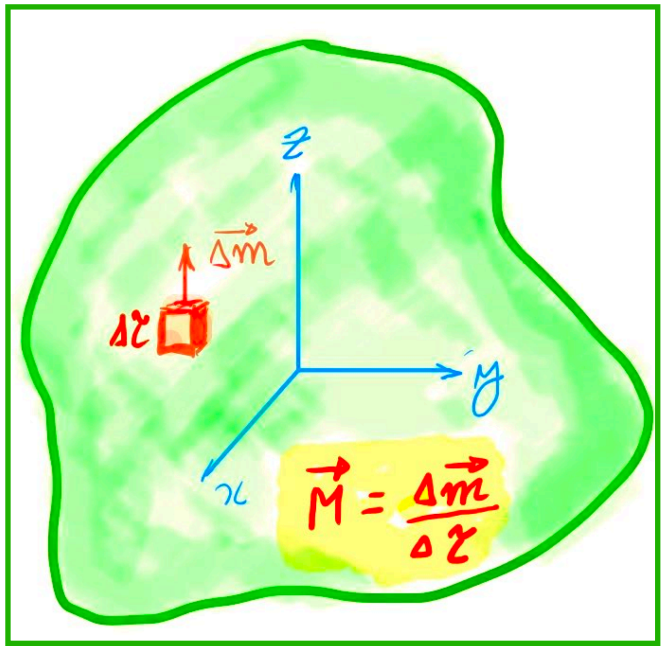
Magnetização



$$\vec{\nabla} \times \overbrace{\left(\vec{B} - \mu_0 \vec{M}\right)}^{\mu_0 \vec{H}} = \mu_0 \vec{J}_f$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$$

Magnetização



$$\vec{\nabla} \times \overbrace{\left(\vec{B} - \mu_0 \vec{M}\right)}^{\mu_0 \vec{H}} = \mu_0 \vec{J}_f$$

$$\vec{\nabla} \times \vec{H} = \vec{J}_f$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$$

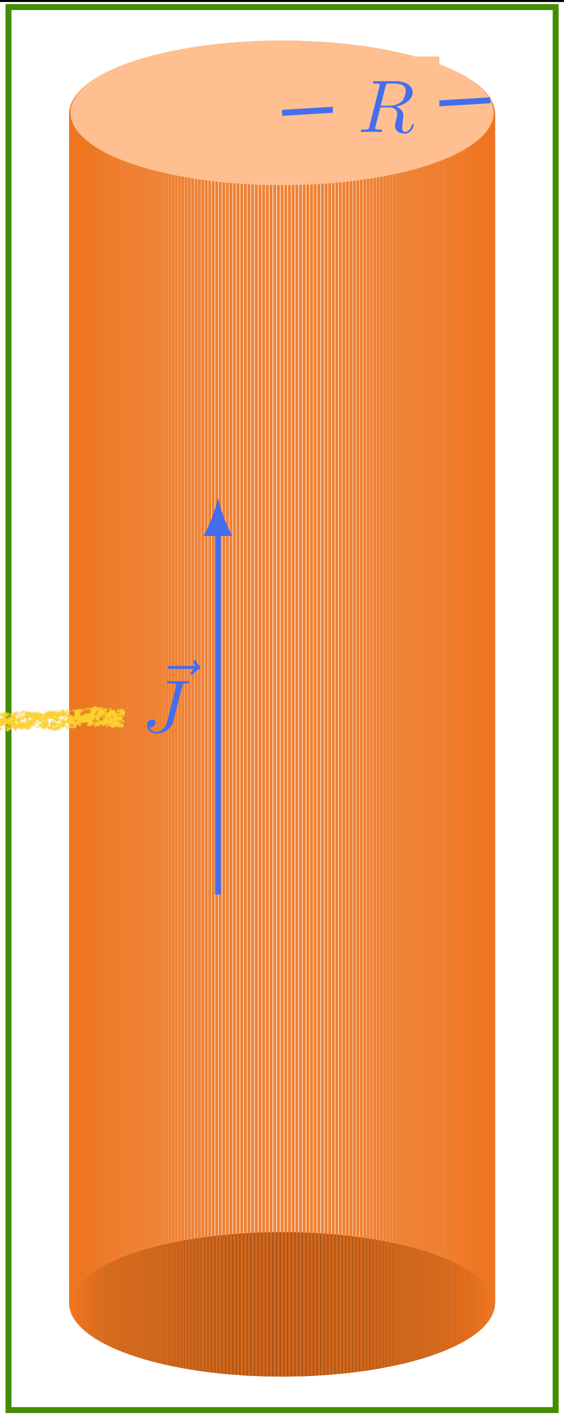
$$\vec{B} = \mu_0(\vec{H} + \vec{M})$$

Pratique o que aprendeu

$$\vec{\nabla} \times \vec{H} = \vec{J}_f$$

- ENCONTRAR CAMPO $\vec{H}$, DENTRO E FORA DO FIO
- PROBLEMA TEM SIMETRIA CILÍNDRICA
  - MAGNETIZAÇÃO TEM DIREÇÃO DO CAMPO MAGNÉTICO (E SENTIDO OPOSTO PQ COBRE É DIAMAGNÉTICO)
  - SIMETRIA É A MESMA QUE HAVERIA SE CORRENTE SE PROPAGASSE NO VÁCUO
  - LINHAS DE $\vec{B}$, $\vec{H}$ E $\vec{M}$ SÃO CIRCULARES EM TORNO DO EIXO DO FIO

DENSIDADE UNIFORME DE CORRENTE



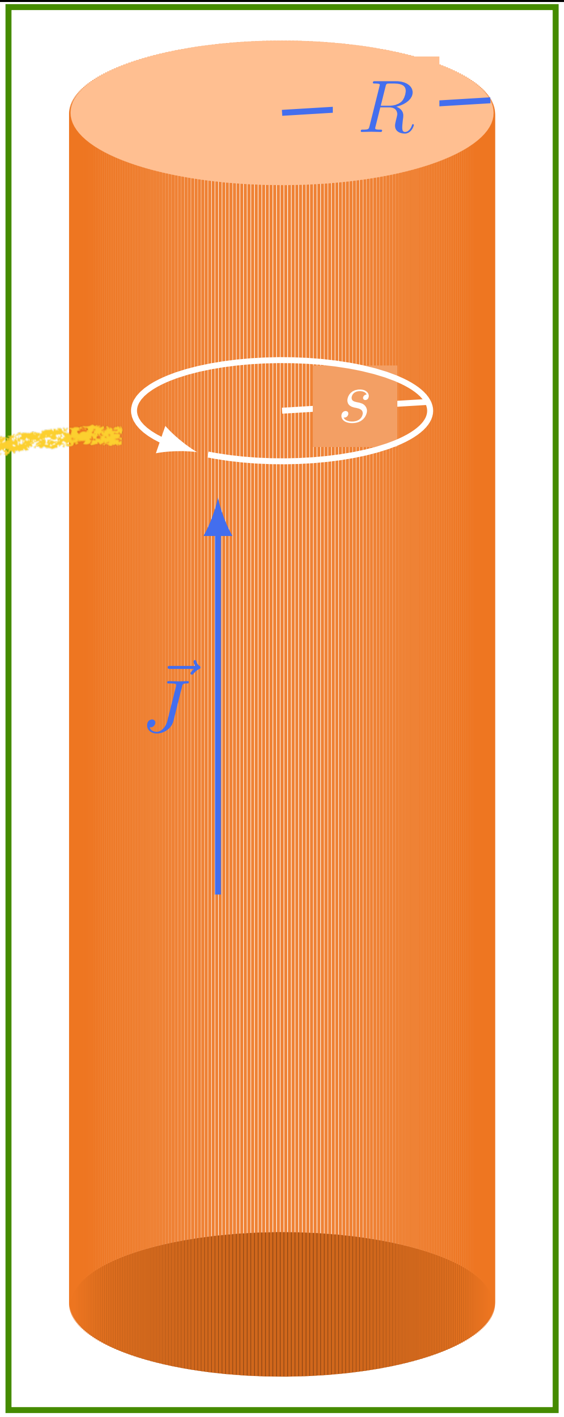
Pratique o que aprendeu

$$\vec{\nabla} \times \vec{H} = \vec{J}_f$$

$$\oint \vec{H} \cdot \mathrm{d}\vec{\ell} = \int \vec{J}_f \cdot \mathrm{d}\vec{a}$$

LEI DE AMPÈRE
NA
FORMA
INTEGRAL

CIRCUITO PARA
APLICAÇÃO DA
LEI DE AMPÈRE



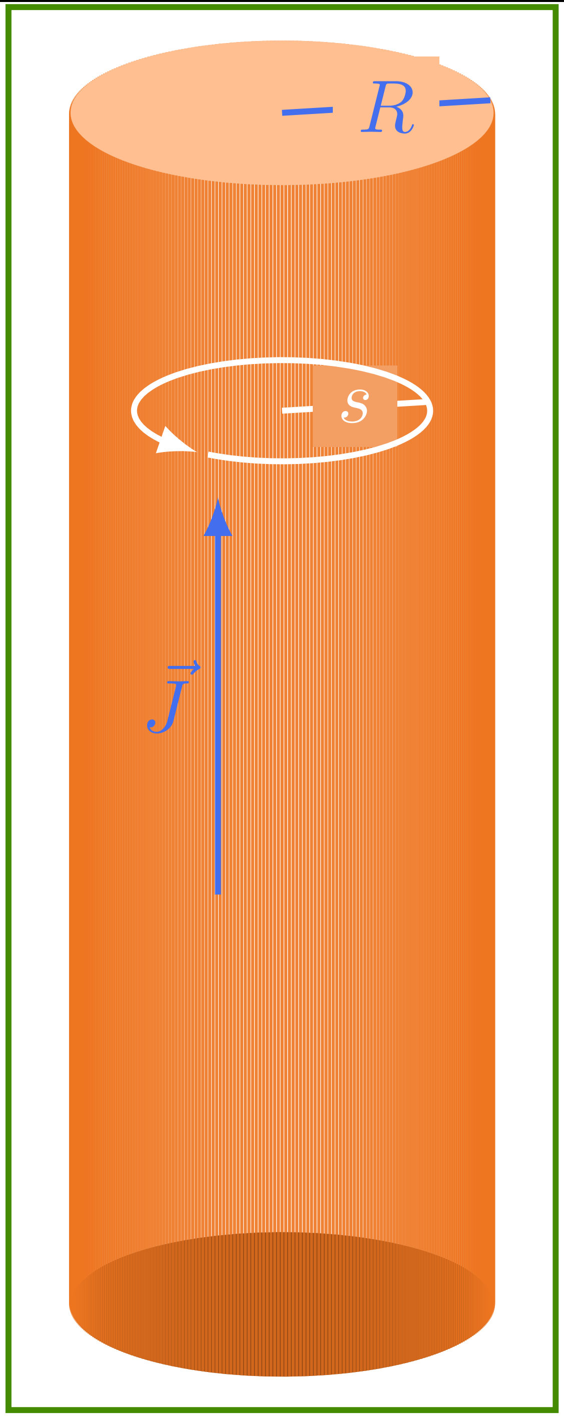
Pratique o que aprendeu

$$\vec{\nabla} \times \vec{H} = \vec{J}_f$$

$$\oint \vec{H} \cdot \mathrm{d}\vec{\ell} = \int \vec{J}_f \cdot \mathrm{d}\vec{a}$$

$$H \oint d\ell = J \int da$$

$$H 2\pi s = J \pi s^2 \qquad (s \leq R)$$



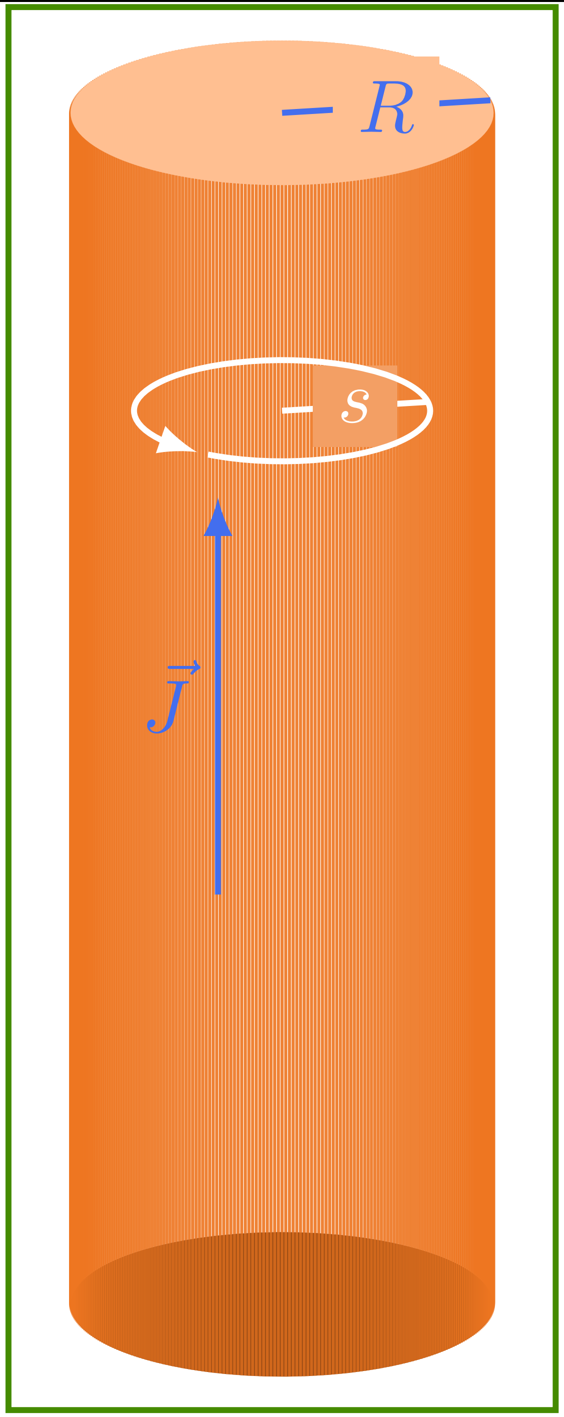
Pratique o que aprendeu

$$\vec{\nabla} \times \vec{H} = \vec{J}_f$$

$$\oint \vec{H} \cdot \mathrm{d}\vec{\ell} = \int \vec{J}_f \cdot \mathrm{d}\vec{a}$$

$$H 2\pi s = J\pi s^2 \qquad (s \leq R)$$

$$\Rightarrow H = J\frac{s}{2}$$



Pratique o que aprendeu

$$\vec{\nabla} \times \vec{H} = \vec{J}_f$$

$$\oint \vec{H} \cdot \mathrm{d}\vec{\ell} = \int \vec{J}_f \cdot \mathrm{d}\vec{a}$$

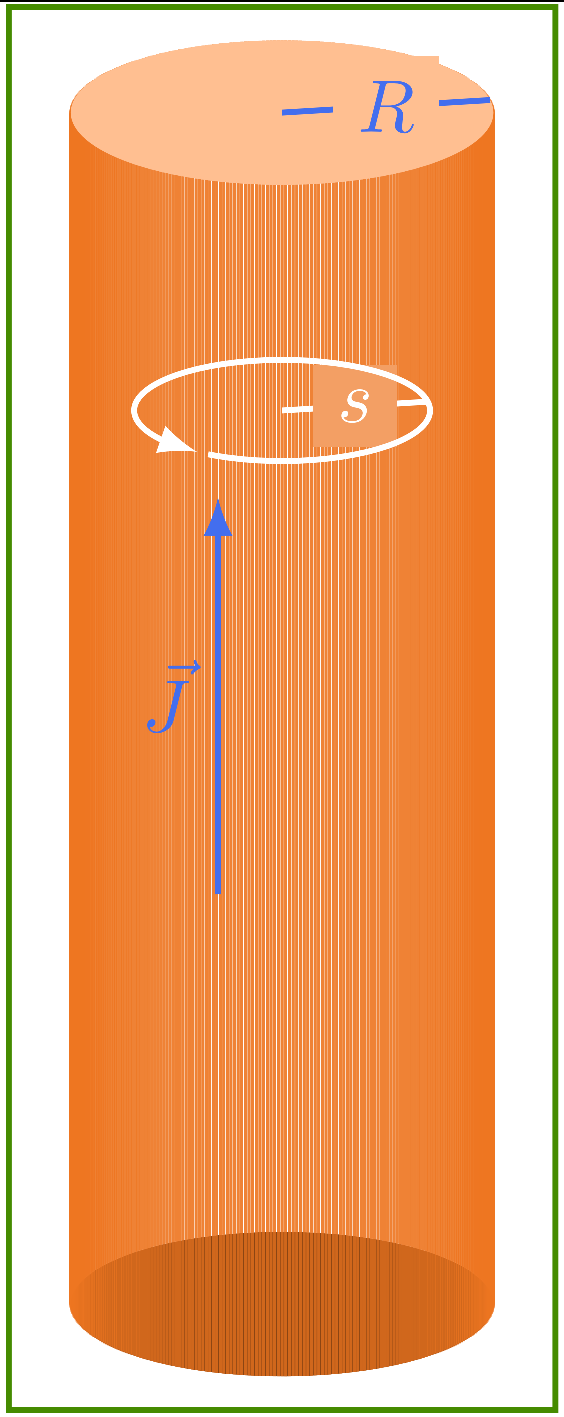
$$H 2\pi s = J \pi s^2 \qquad (s \leq R)$$

$$H = J\frac{s}{2}$$

$$H \oint dl = J \int da$$

SEÇÃO DO FIO, SE $s \geq R$

$$H 2\pi s = J \pi R^2 \qquad (s \geq R)$$



Pratique o que aprendeu

$$\vec{\nabla} \times \vec{H} = \vec{J}_f$$

$$\oint \vec{H} \cdot \mathrm{d}\vec{\ell} = \int \vec{J}_f \cdot \mathrm{d}\vec{a}$$

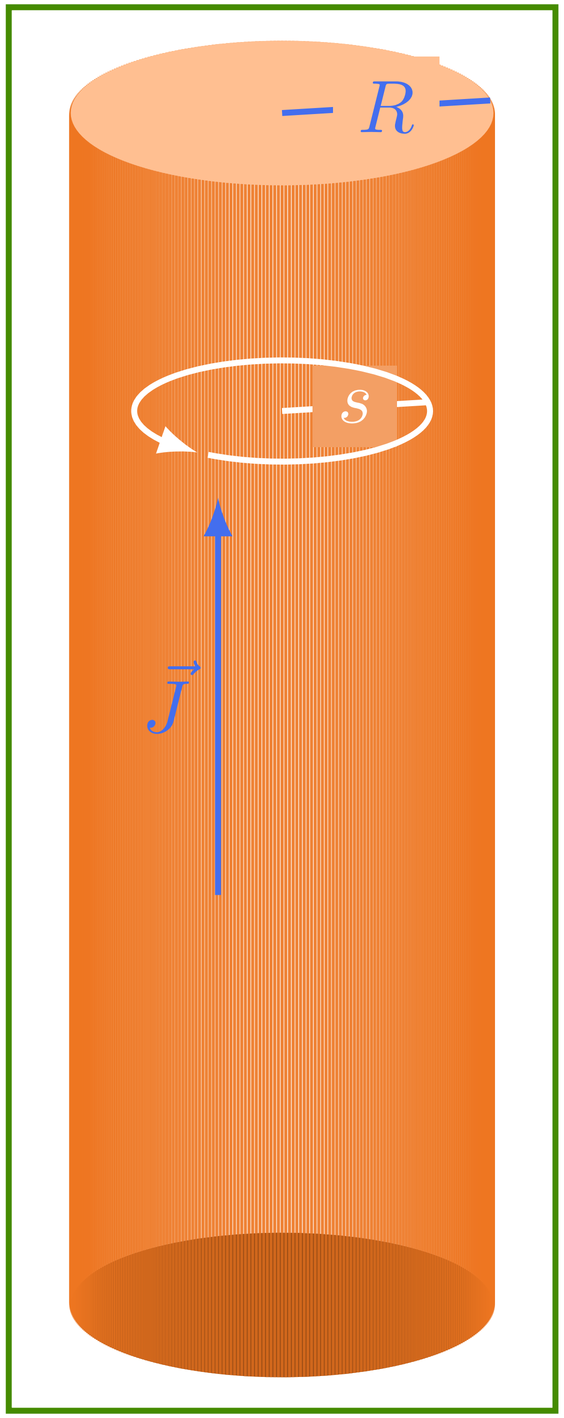
$$H 2\pi s = J\pi s^2 \qquad (s \leq R)$$

$$H = J\frac{s}{2}$$

$$H 2\pi s = J\pi R^2 \qquad (s \geq R)$$

$$H = J\frac{R^2}{2s} \Rightarrow B = \mu_0 H = \frac{JR^2}{2s} = \mu_0 \frac{I}{2\pi s}$$

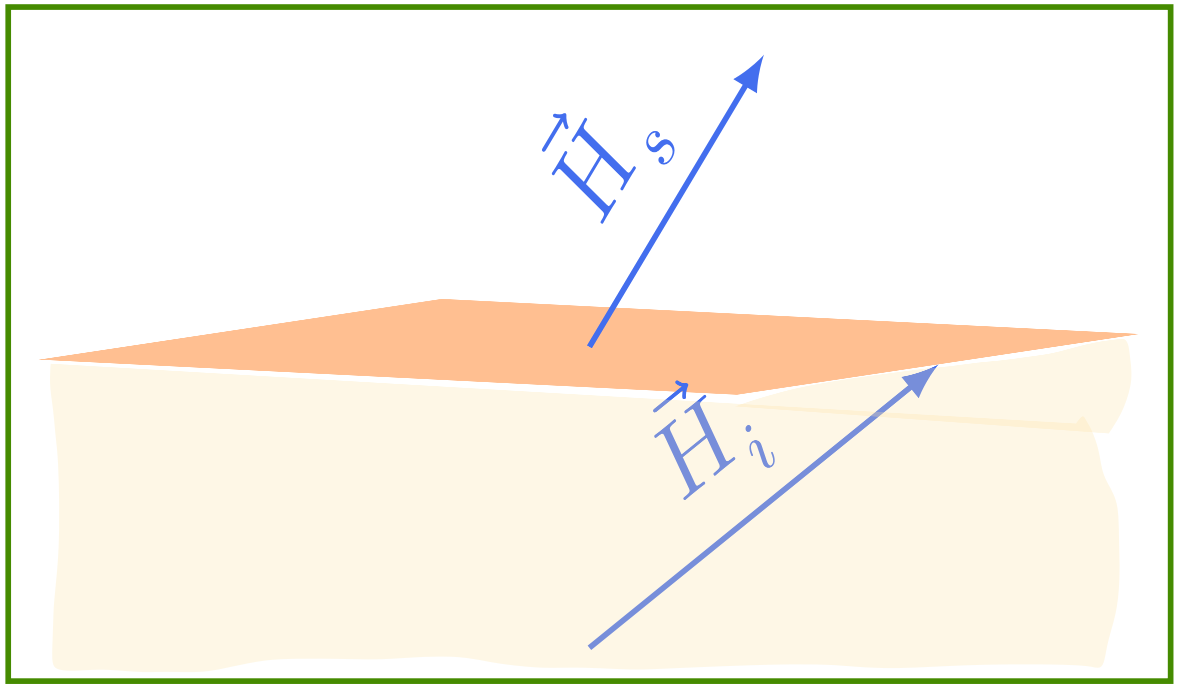
$I = \pi R^2 J$



Condições de contorno

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

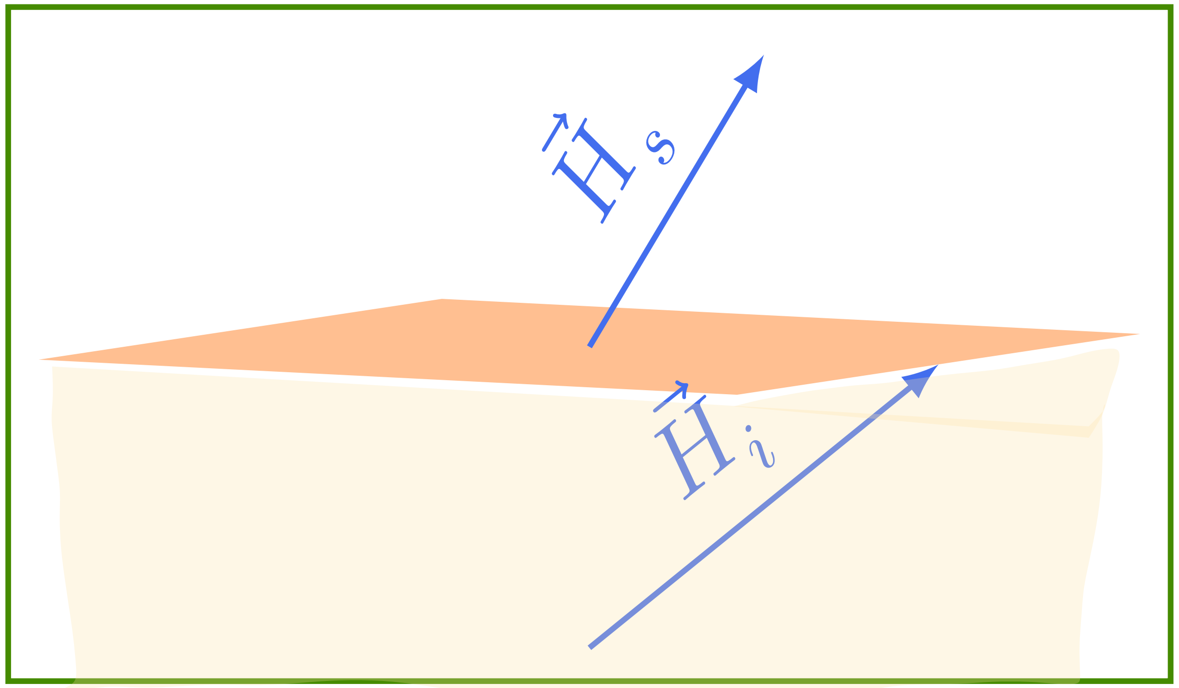
$$\vec{\nabla} \times \vec{H} = \vec{J}_f$$



Condições de contorno

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

$$\vec{\nabla} \times \vec{H} = \vec{J}_f$$

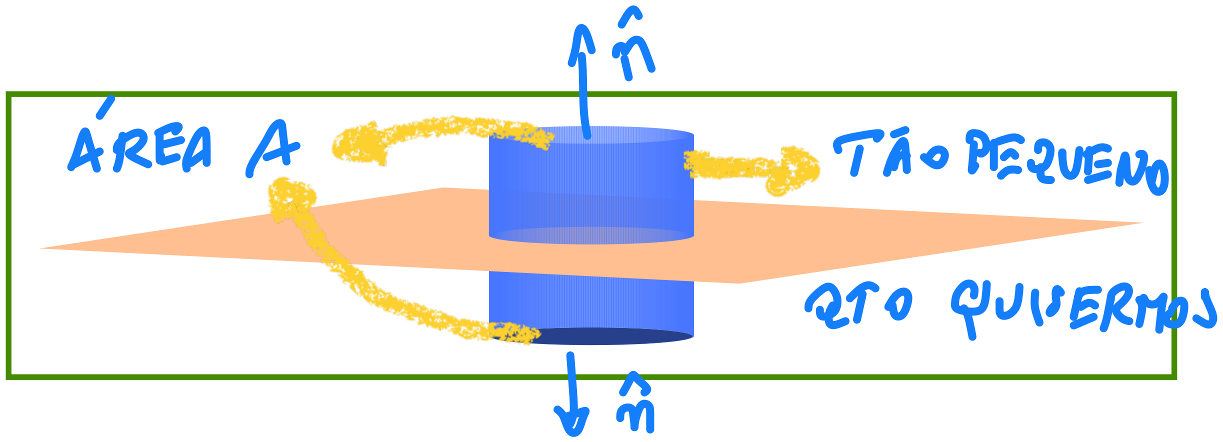


$$\int \vec{B} \cdot \mathrm{d}\vec{a} = 0$$

INTEGRAL NOS TAMPOS SUPERIOR E INFERIOR

$$\int \vec{B} \cdot d\vec{a} = B_{\perp s} A - B_{\perp i} A$$

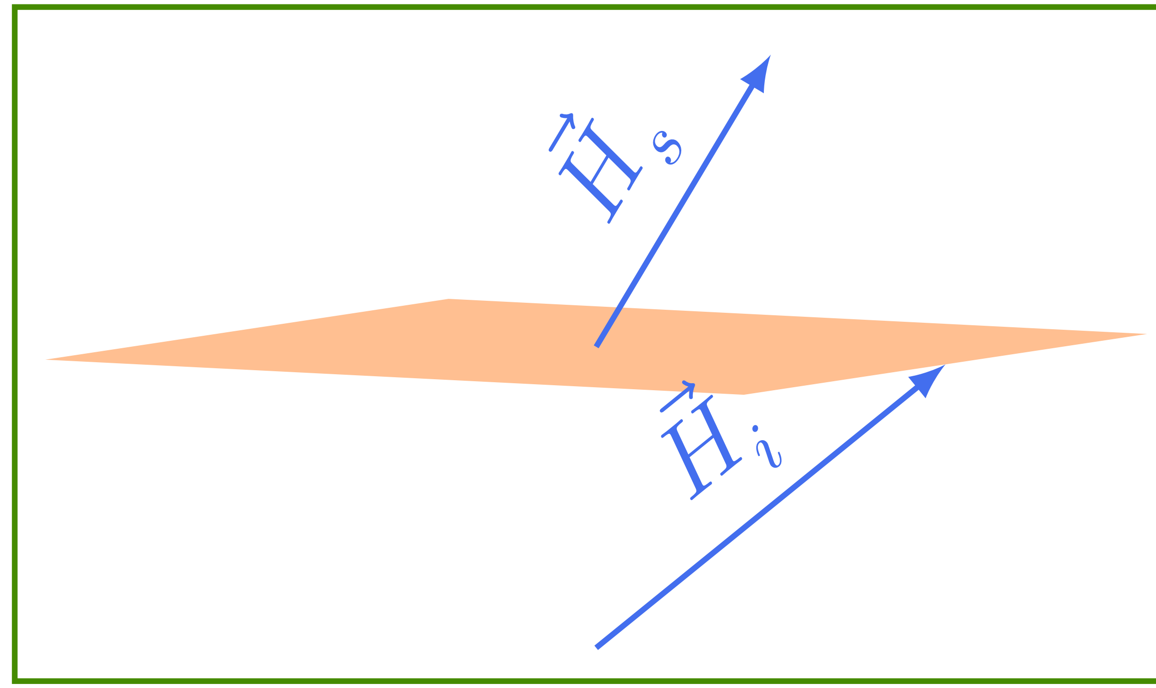
$$B_{\perp s} = B_{\perp i}$$



Condições de contorno

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

$$\vec{\nabla} \times \vec{H} = \vec{J}_f$$



$$\int \vec{B} \cdot d\vec{a} = 0$$

$$B_{\perp s} = B_{\perp i}$$

$$\int \vec{H} \cdot d\vec{\ell} = \int \vec{J}_f \cdot d\vec{a}$$

$K_f\, \delta(z)$

STOKES

$$-H_{s\parallel}\, \ell + H_{i\parallel}\, \ell = -K_f\, \ell$$

SE CIRCUITO $\perp$ $\vec{K}_f$

$$-H_{s\parallel}\, \ell + H_{i\parallel}\, \ell = 0$$

SE CIRCUITO // $\vec{K}_f$

$$\vec{H}_{s\parallel} - \vec{H}_{i\parallel} = \vec{K}_f \times \hat{n}$$