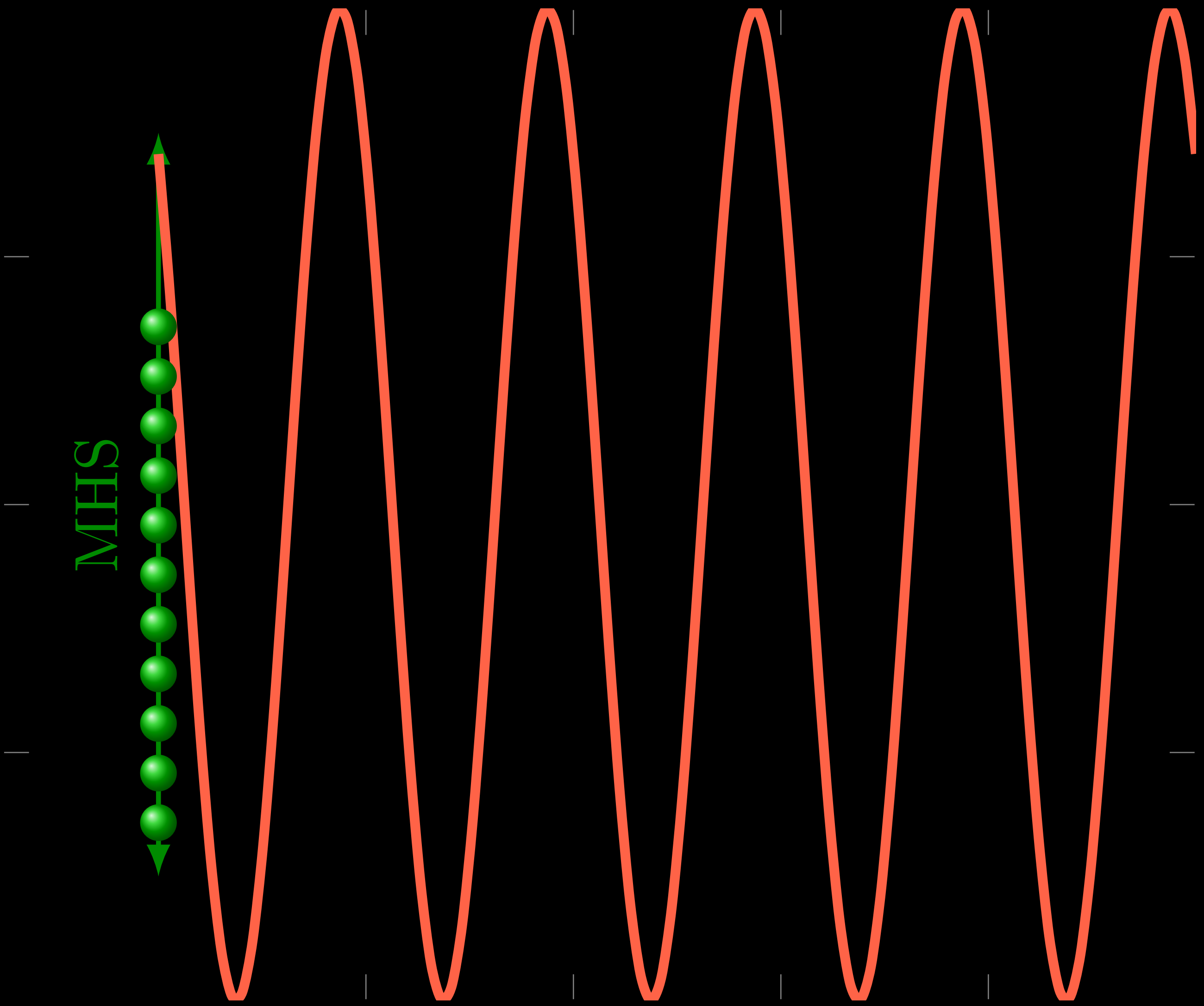



# Física IV

13 outubro 2020

Equações de Maxwell

Energia eletromagnética

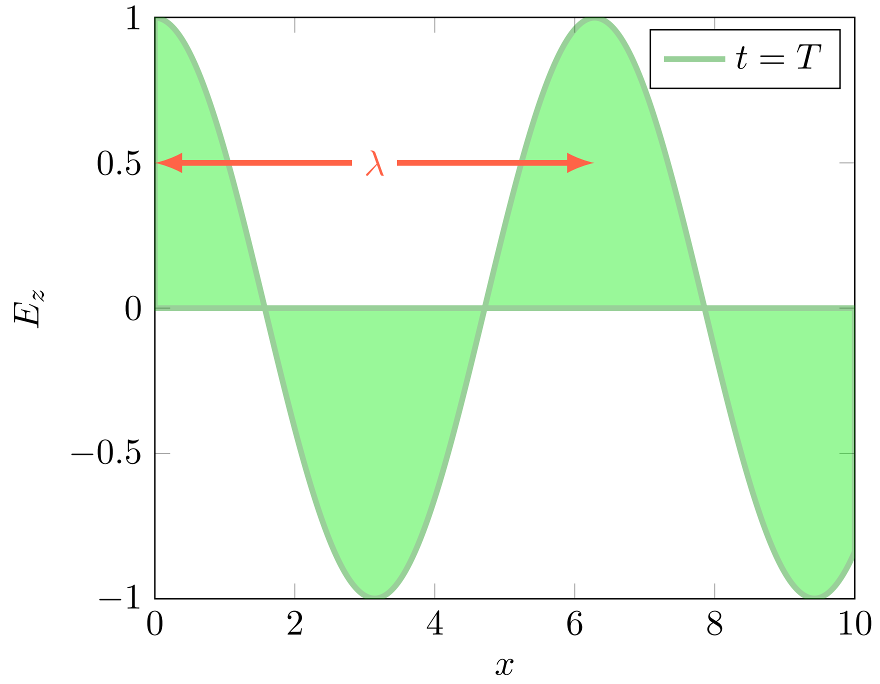
# Equações de Maxwell
# Radiação monocromática

$$\overrightarrow{E}(\vec{r},t) = E_0 \cos(\overrightarrow{k} \cdot \vec{r} - \omega t)\,\hat{z}$$

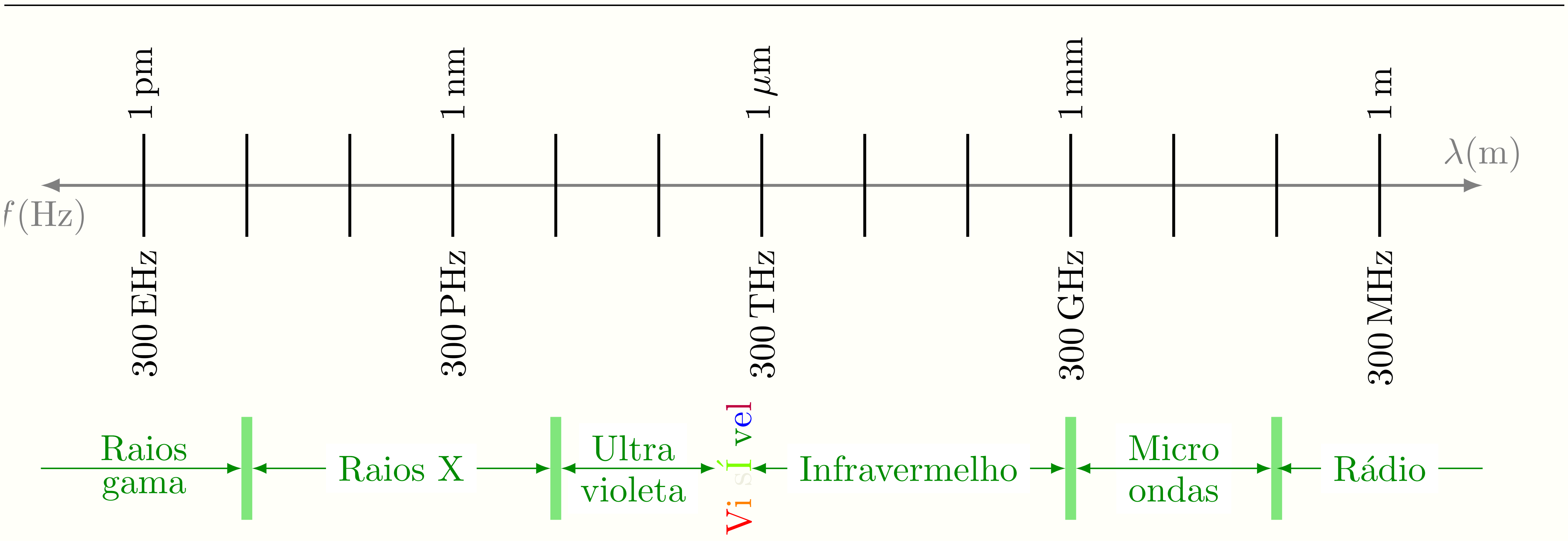
$$\omega = ck \qquad \lambda = cT$$

$$k = \frac{2\pi}{\lambda} \qquad \omega = \frac{2\pi}{T}$$

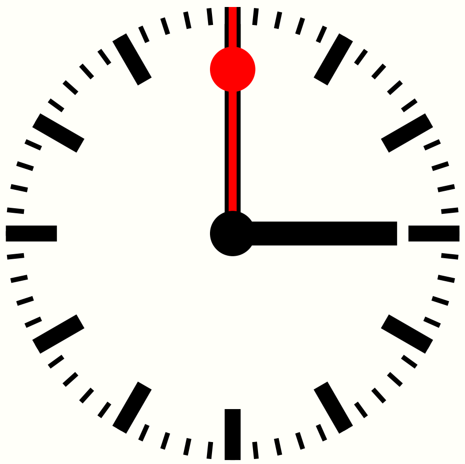
$$f = \frac{1}{T} \qquad \omega = 2\pi f$$

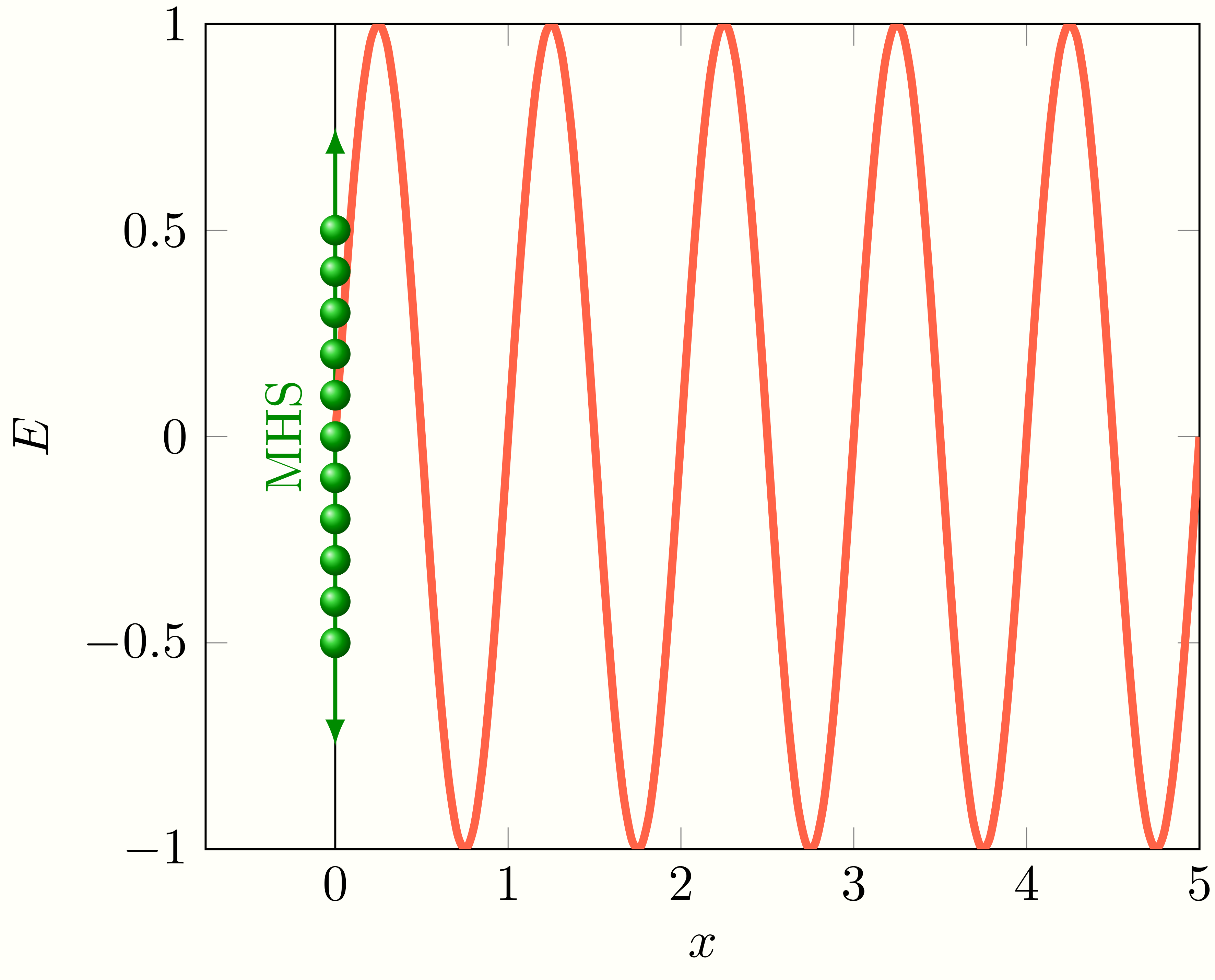


# Equações de Maxwell
# Espaço livre
# Espectro eletromagnético

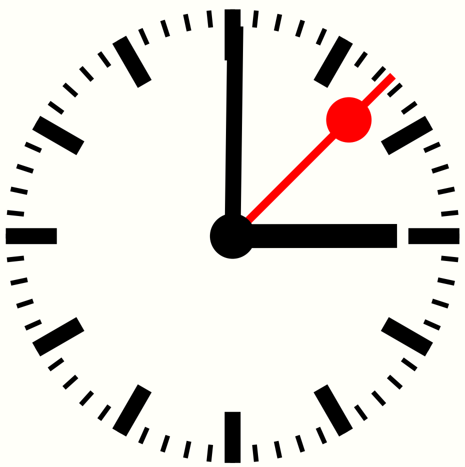


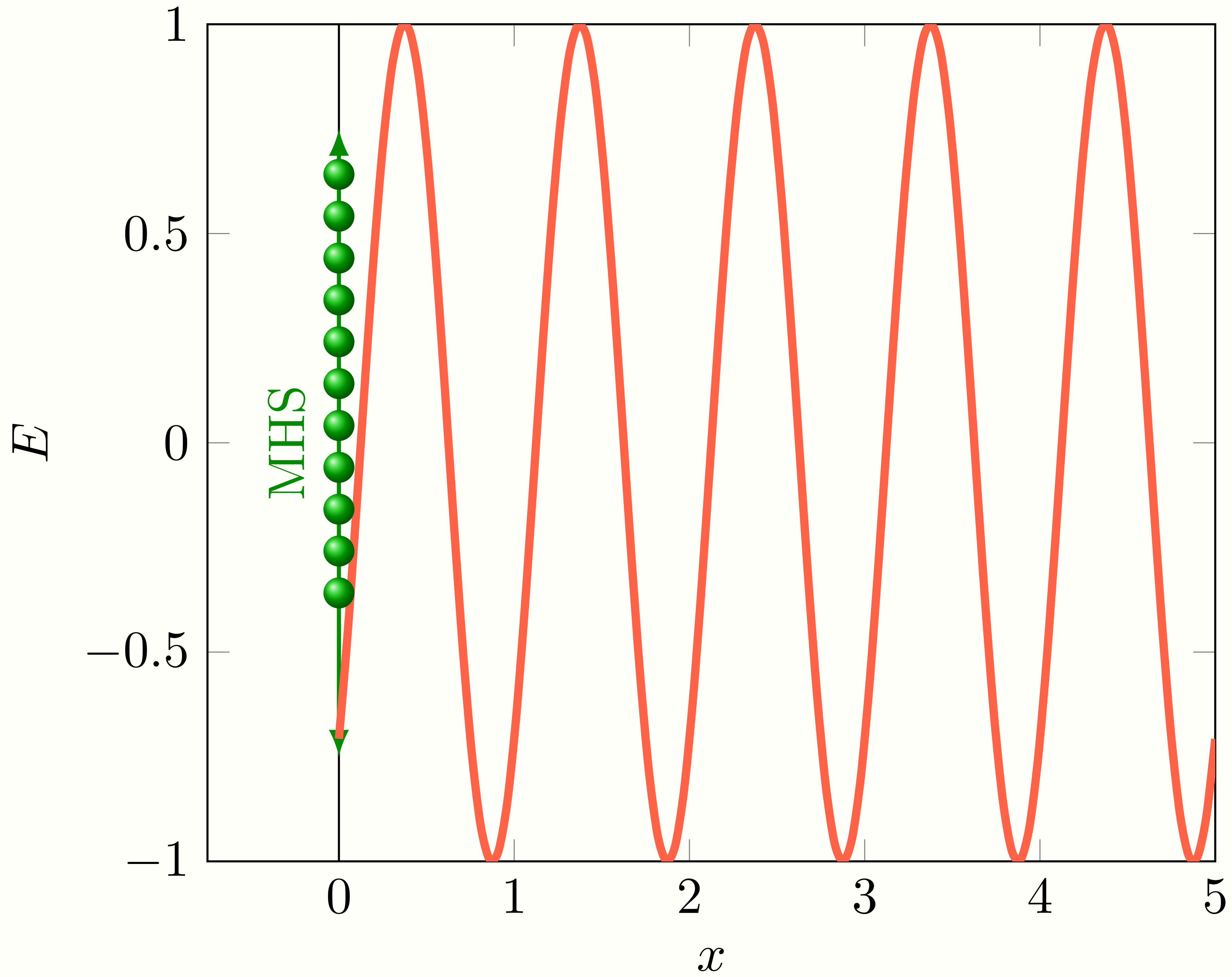
# Equações de Maxwell
# Radiação eletromagnética



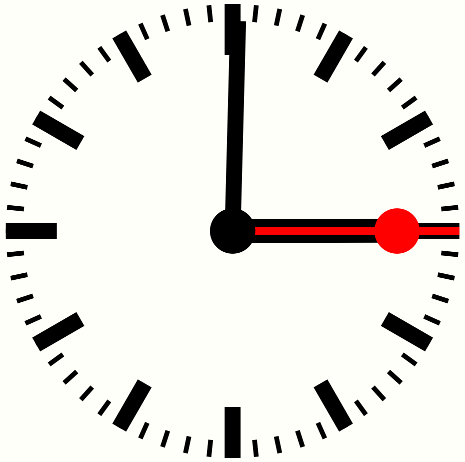


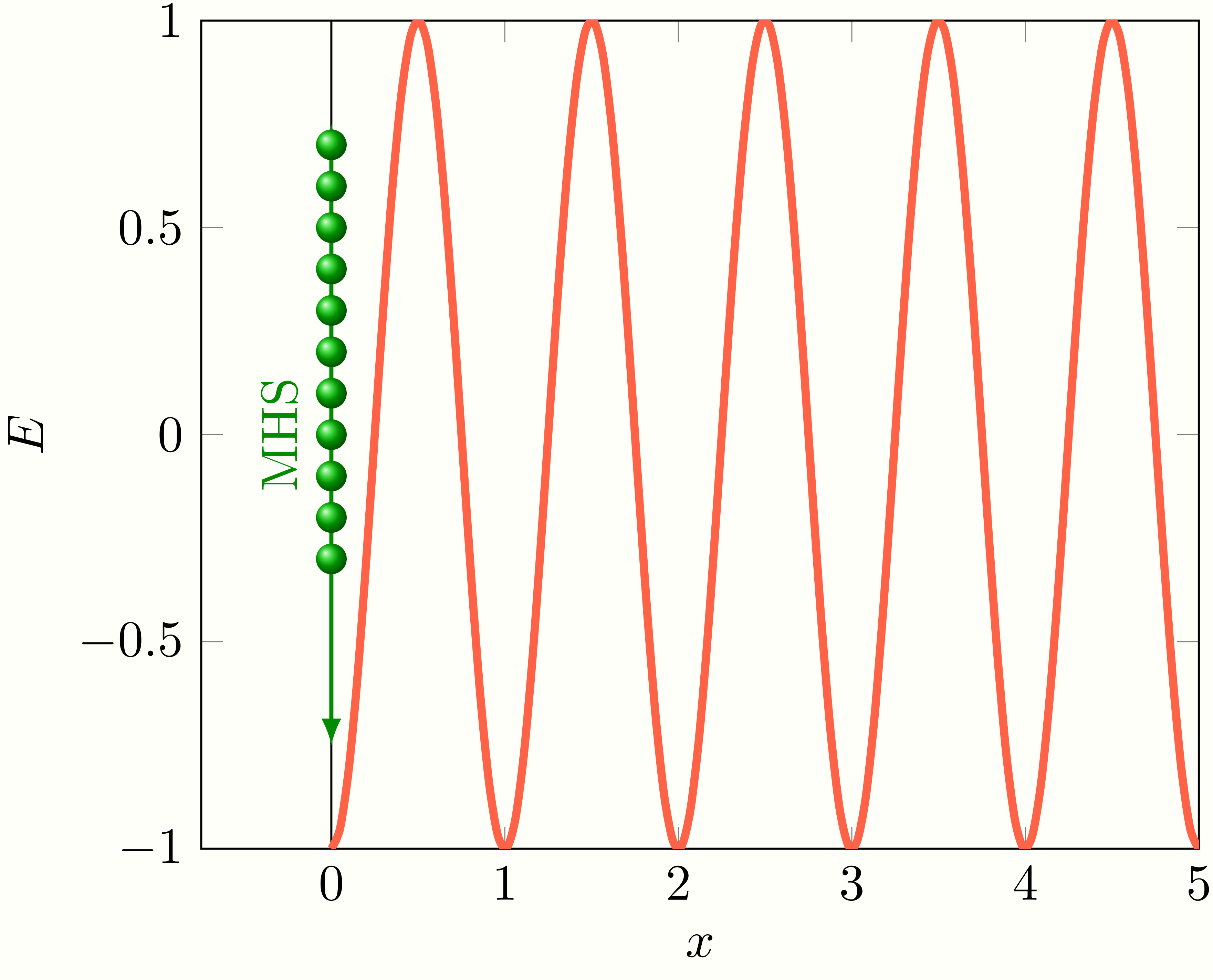
# Equações de Maxwell
# Radiação eletromagnética



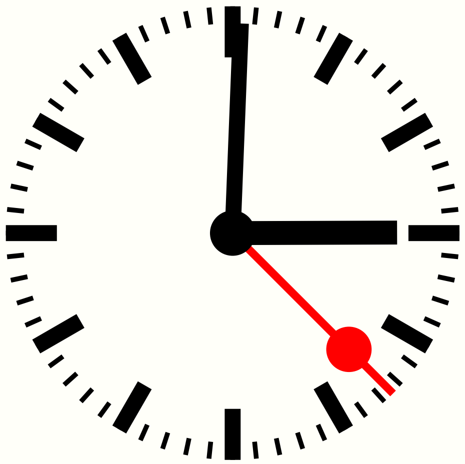


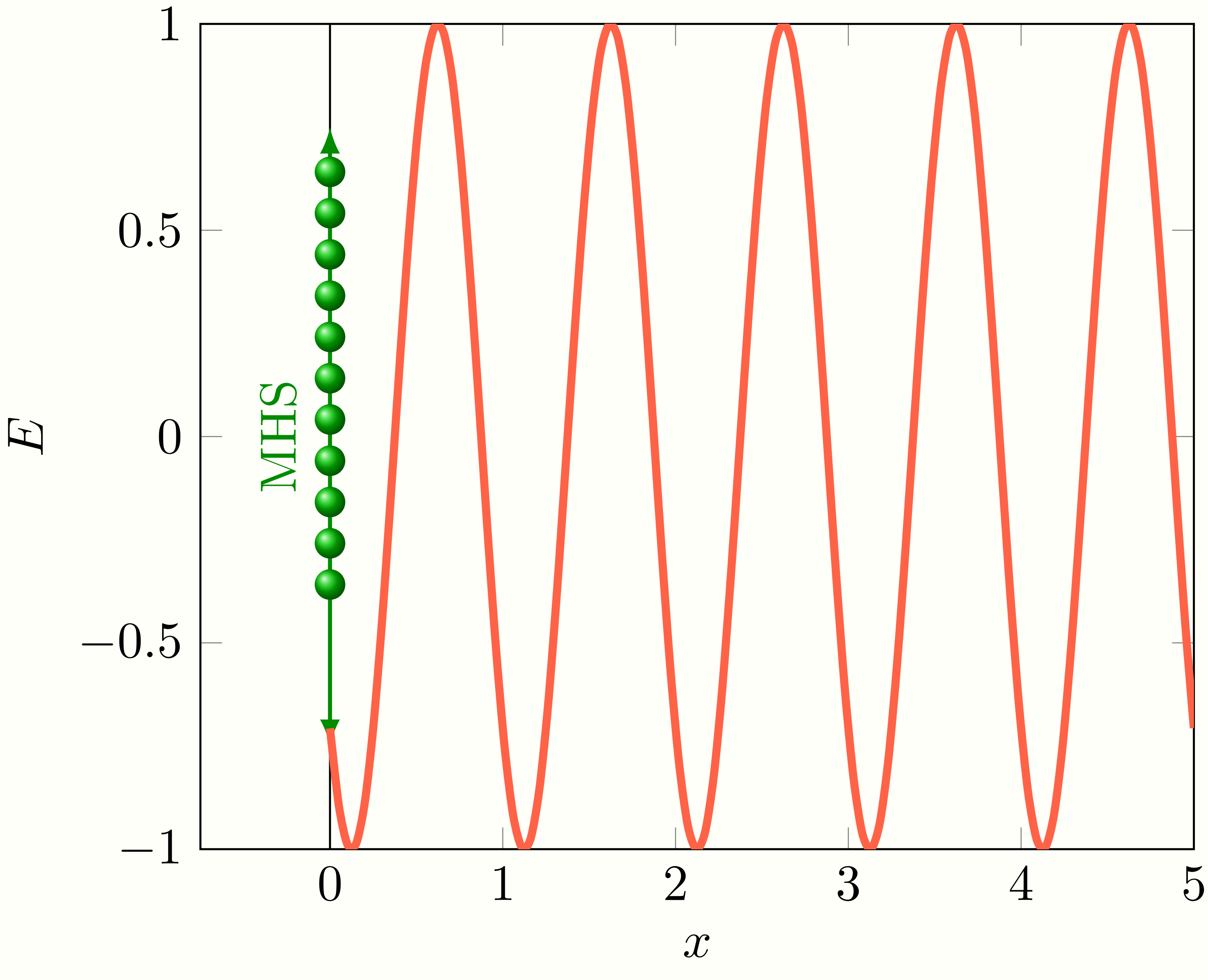
# Equações de Maxwell
# Radiação eletromagnética



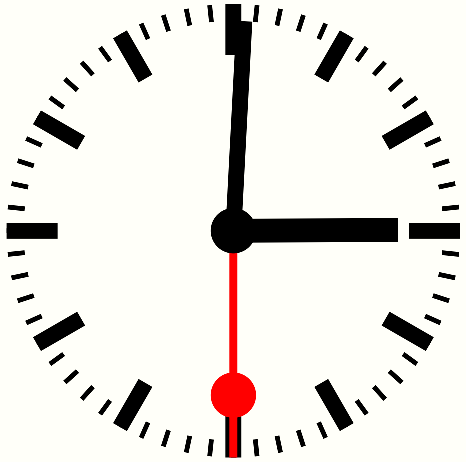


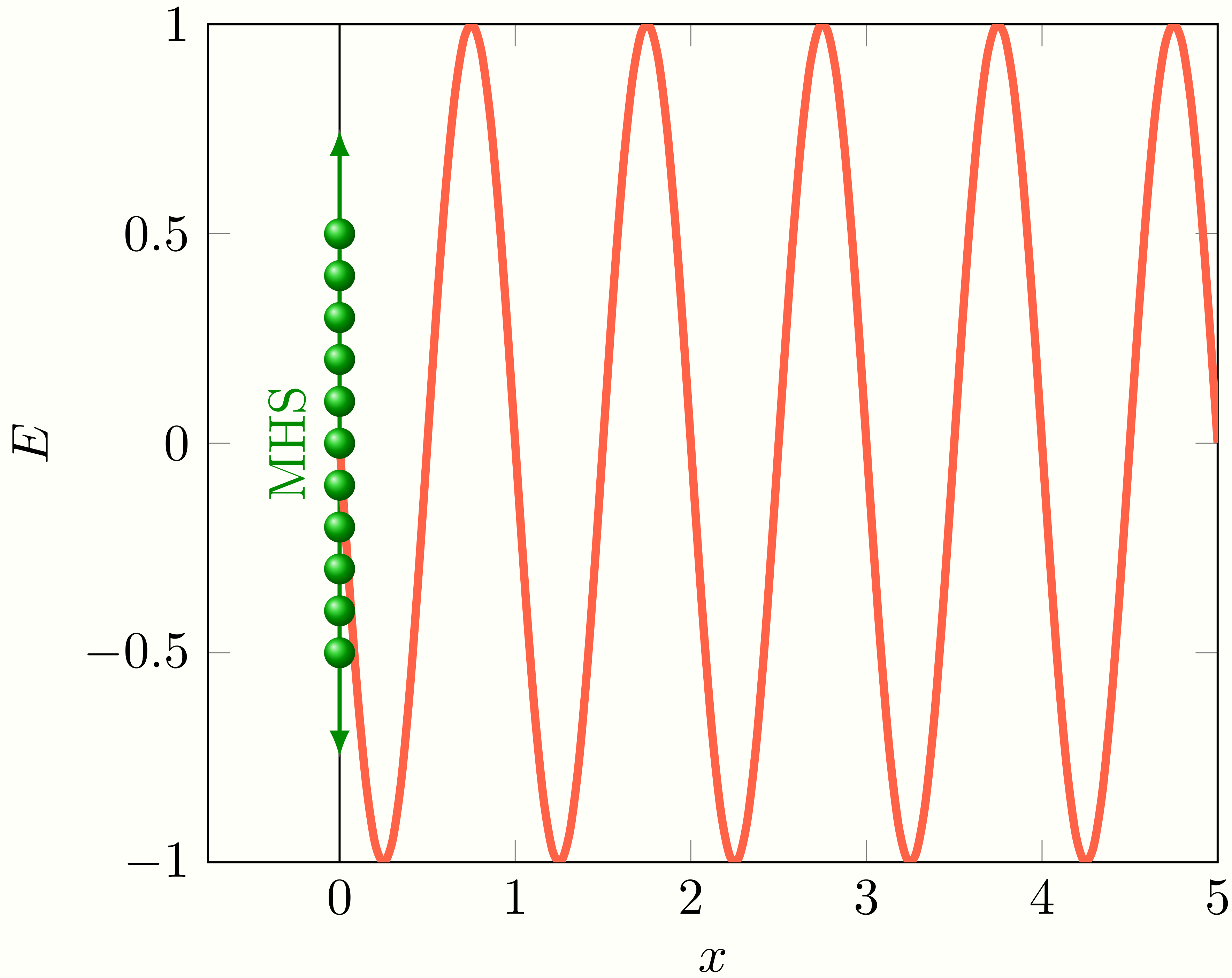
# Equações de Maxwell
# Radiação eletromagnética



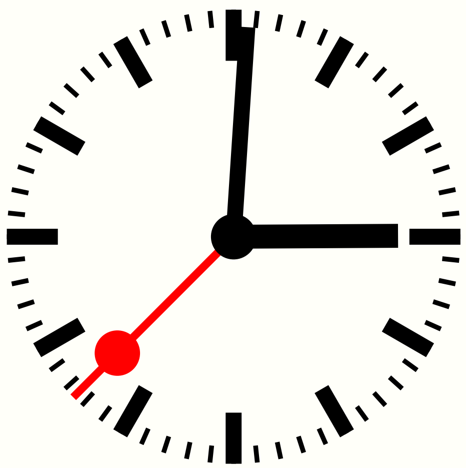


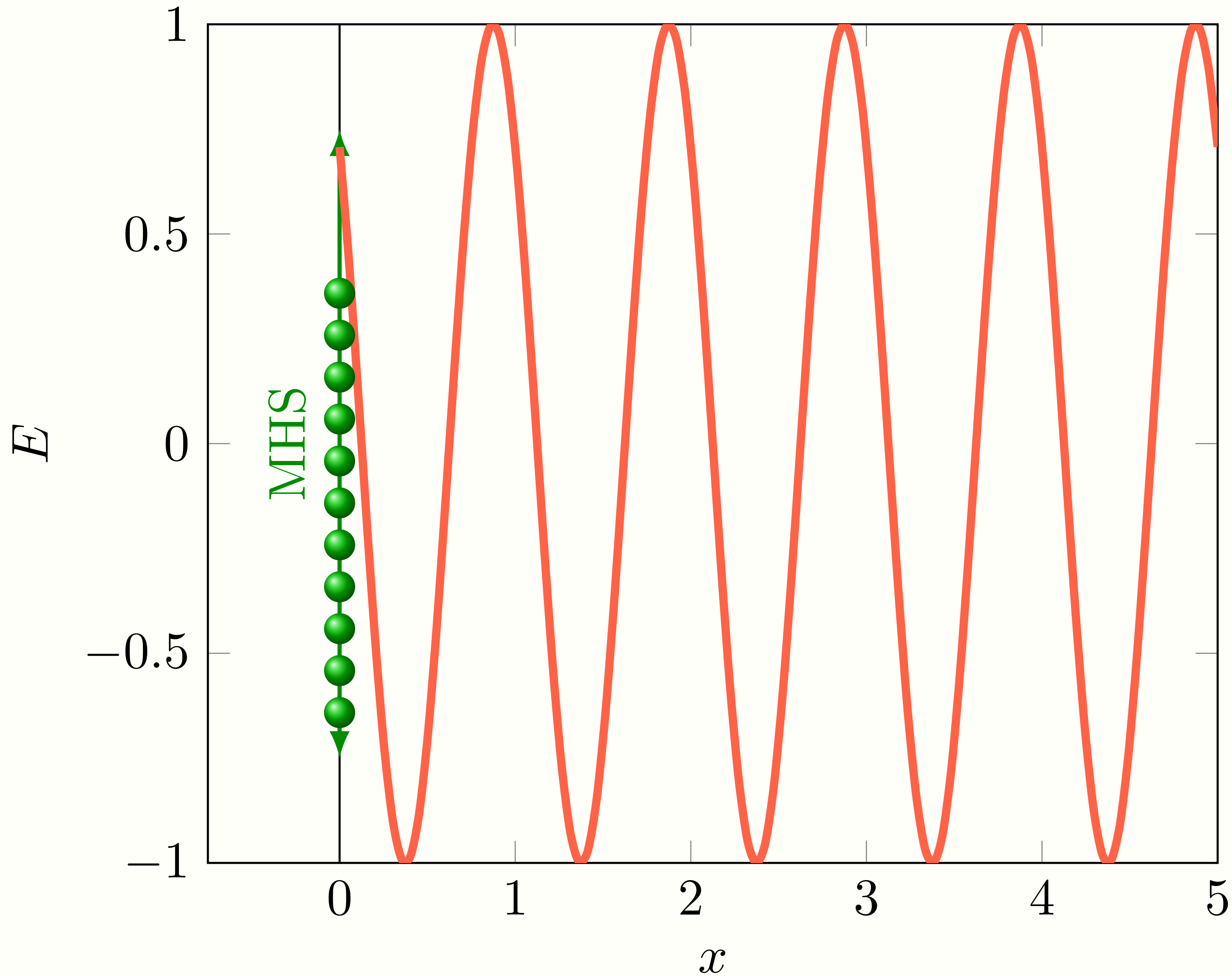
# Equações de Maxwell
# Radiação eletromagnética



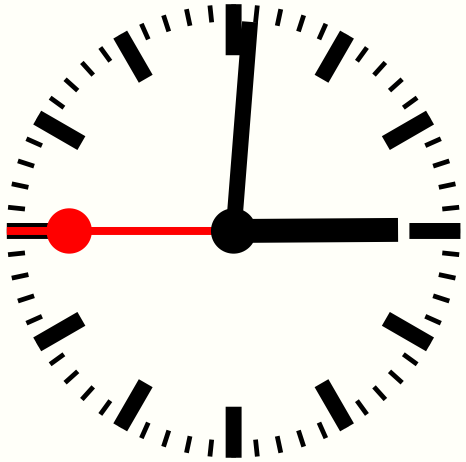


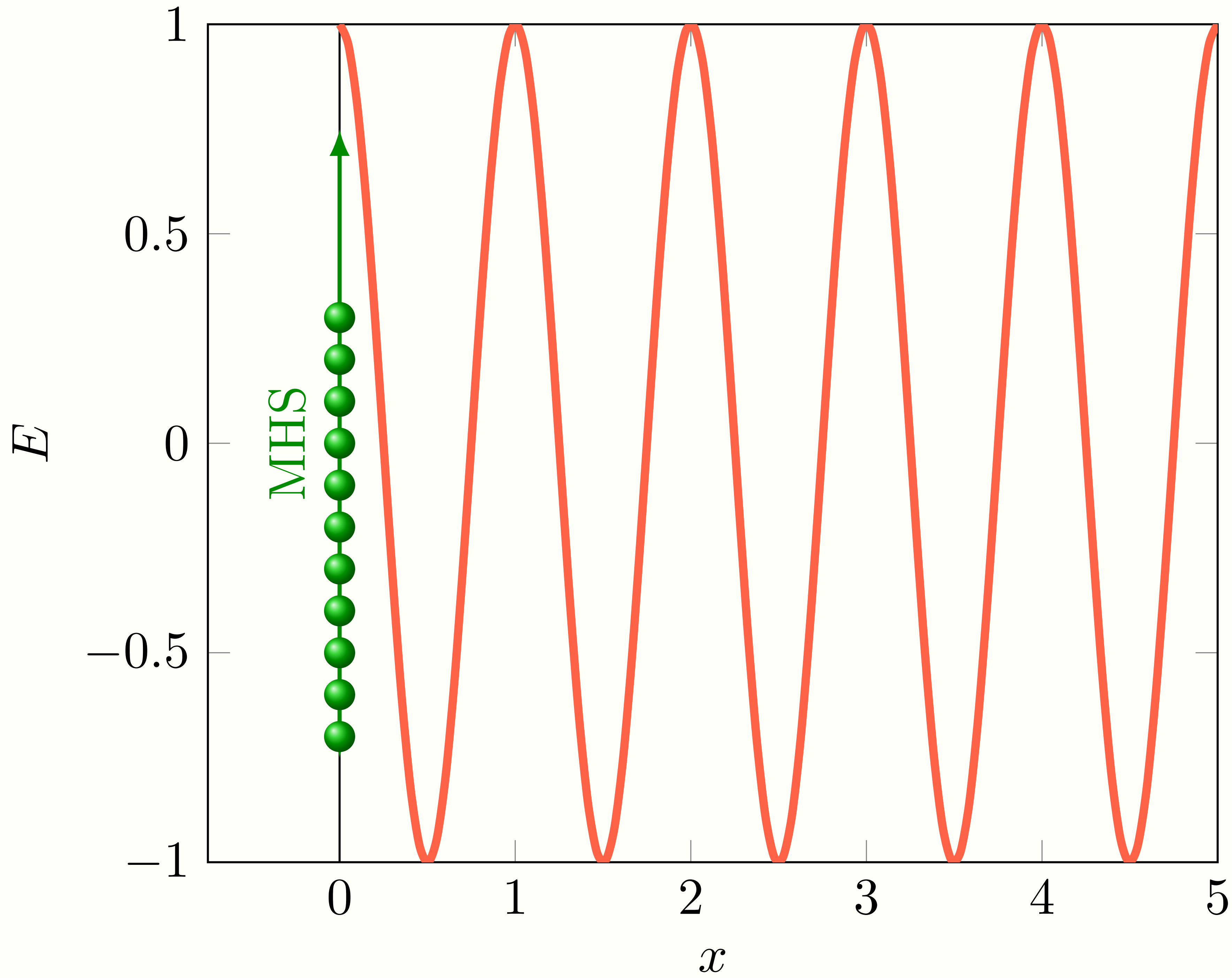
# Equações de Maxwell
# Radiação eletromagnética



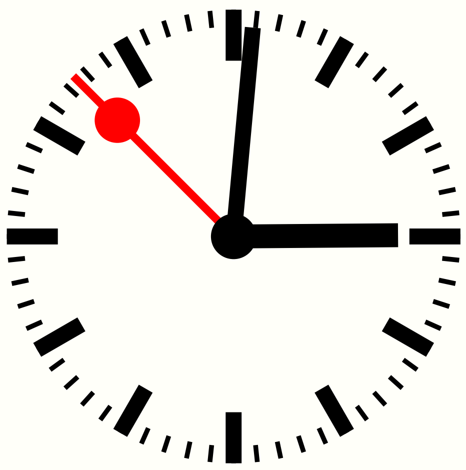


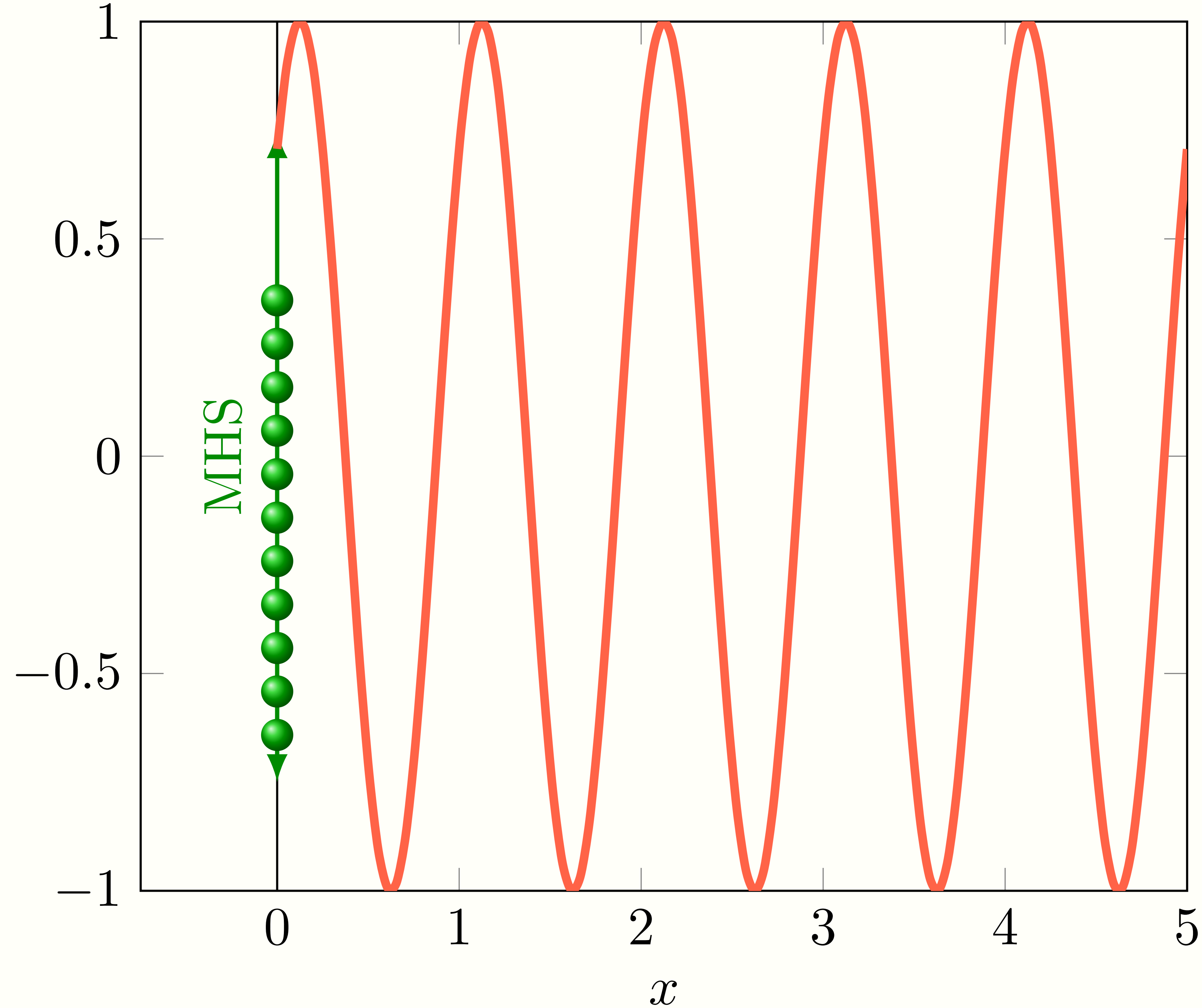
# Equações de Maxwell
# Radiação eletromagnética



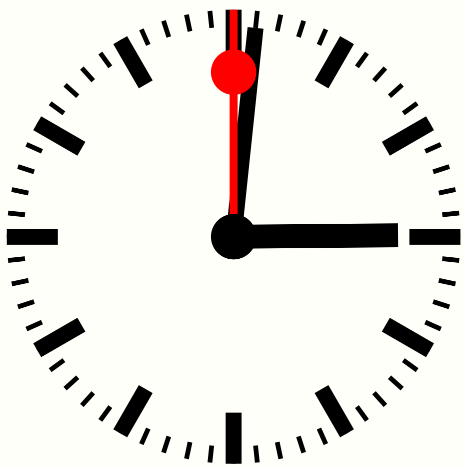


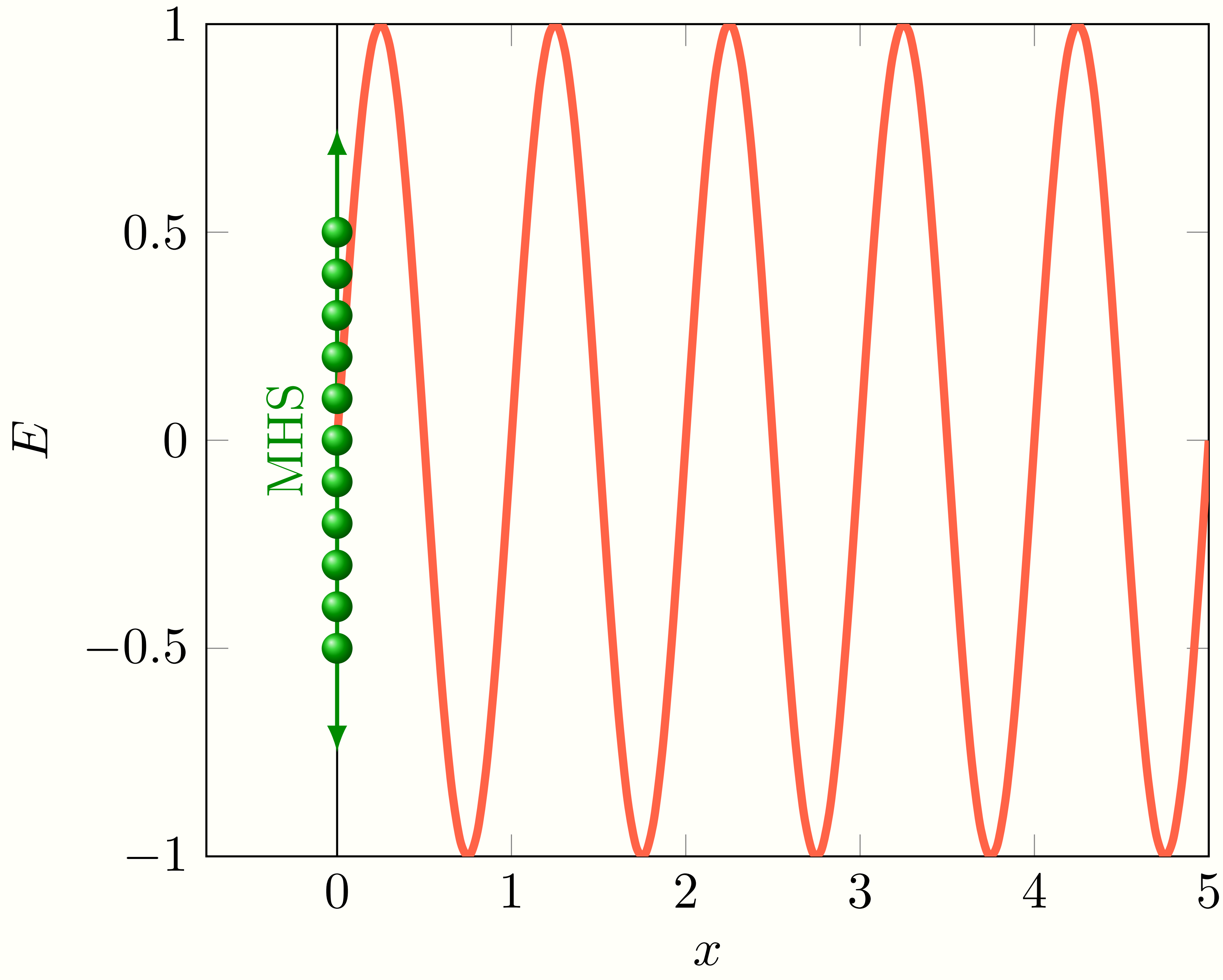
# Equações de Maxwell
# Radiação eletromagnética





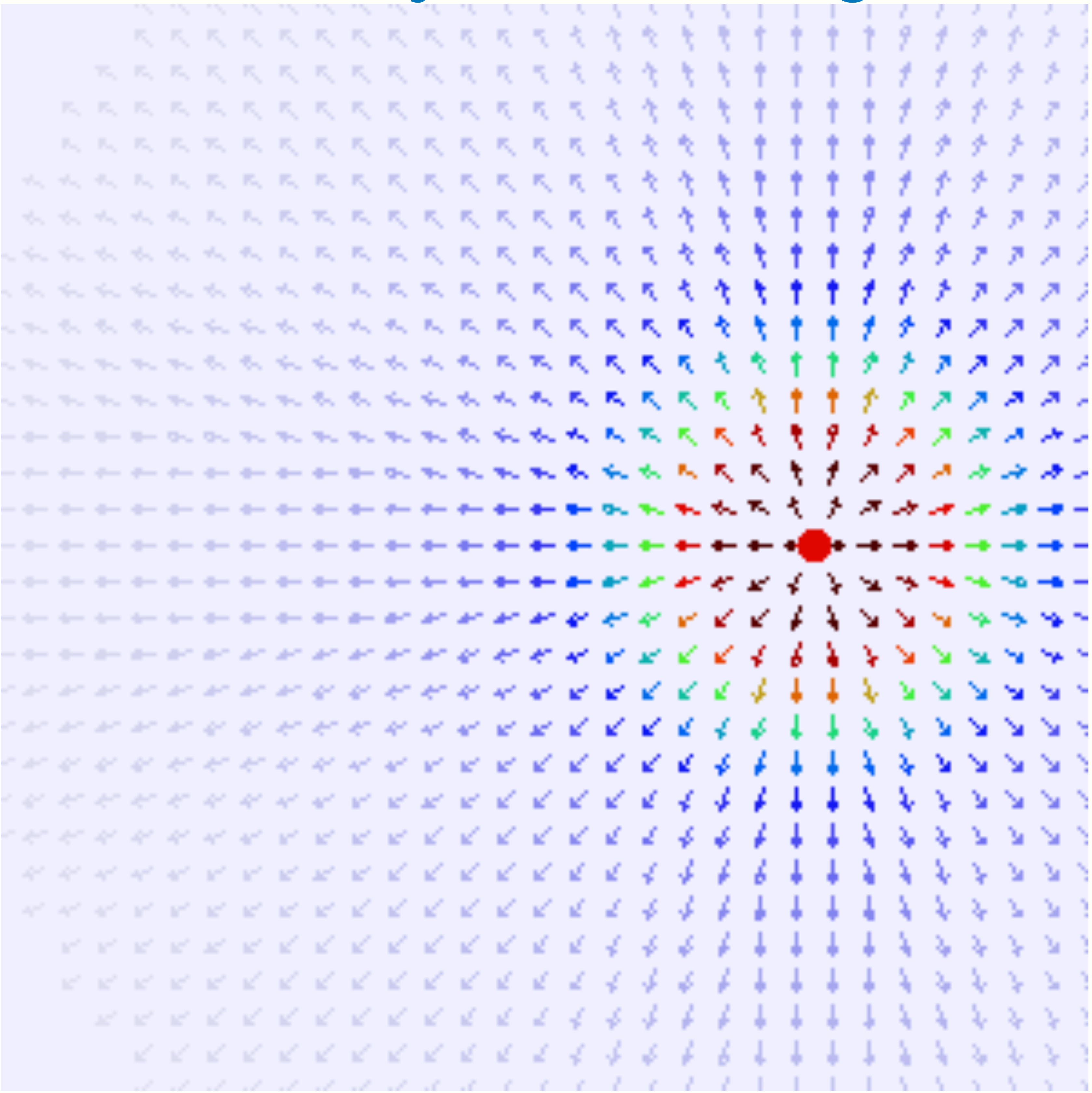
# Equações de Maxwell
# Radiação eletromagnética





# Equações de Maxwell
# Radiação eletromagnética

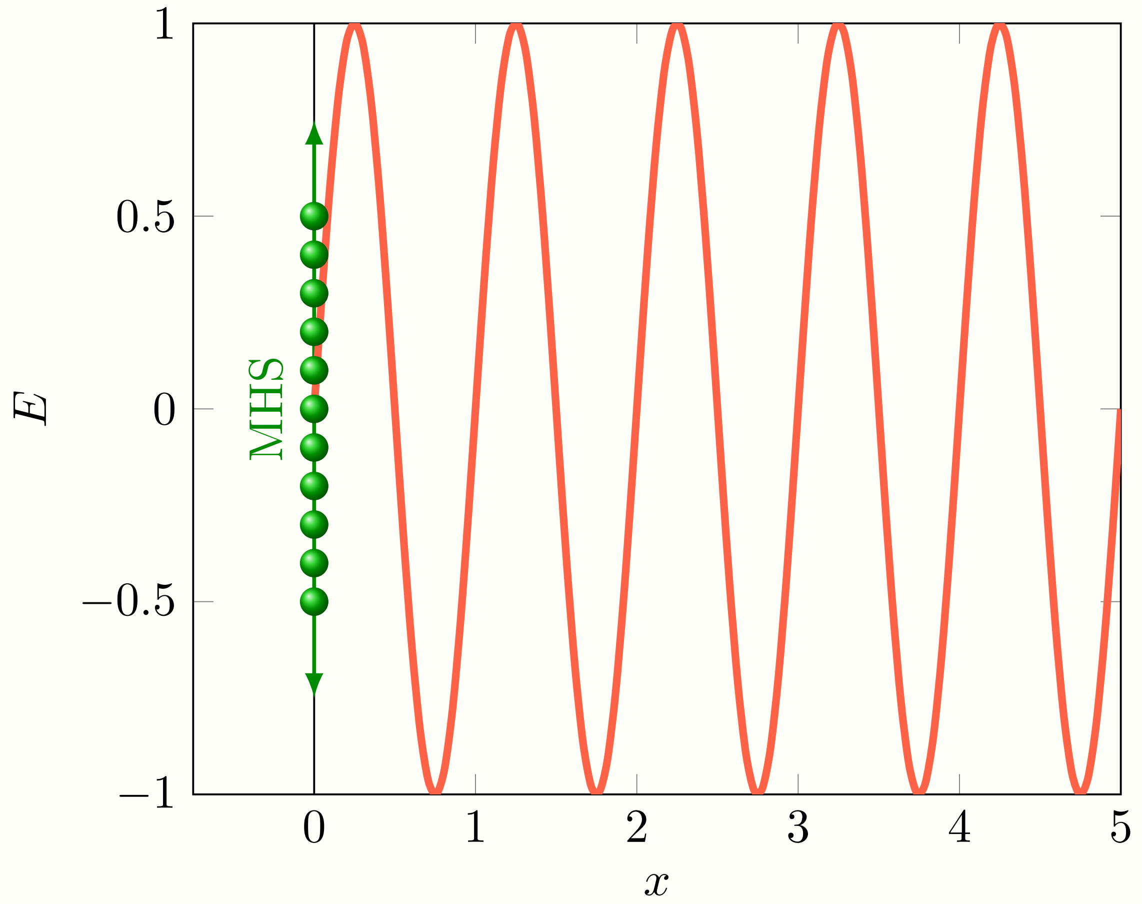
Radiação de carga em movimento harmônico simples



# Equações de Maxwell
# Radiação eletromagnética

$$U = U_E + U_B$$

$$U = ?$$

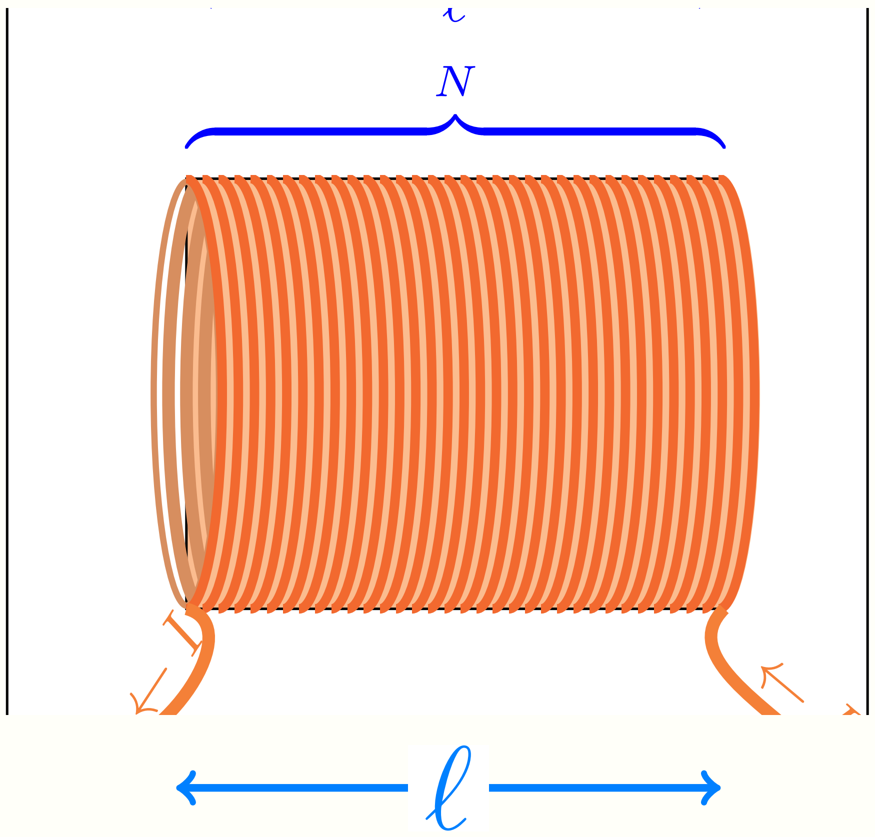


# Equações de Maxwell
# Energia da radiação

$U_B = ?$

$$U = U_E + U_B$$

$$U_B = L\frac{I^2}{2}$$



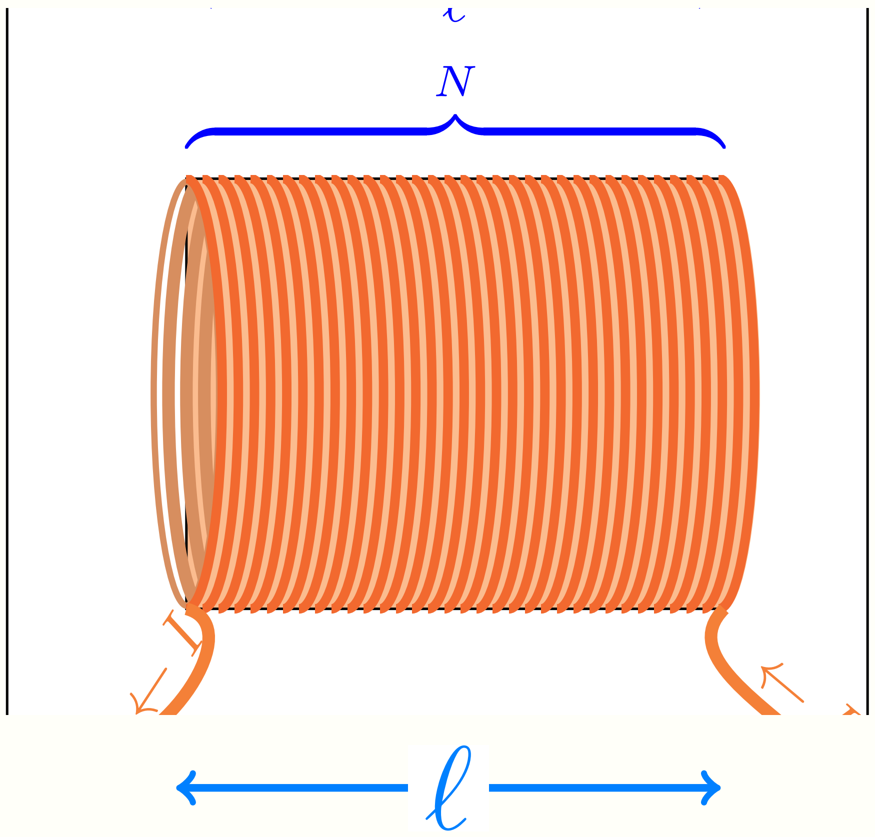
# Equações de Maxwell
# Energia da radiação

$U_B = ?$

$$U = U_E + U_B$$

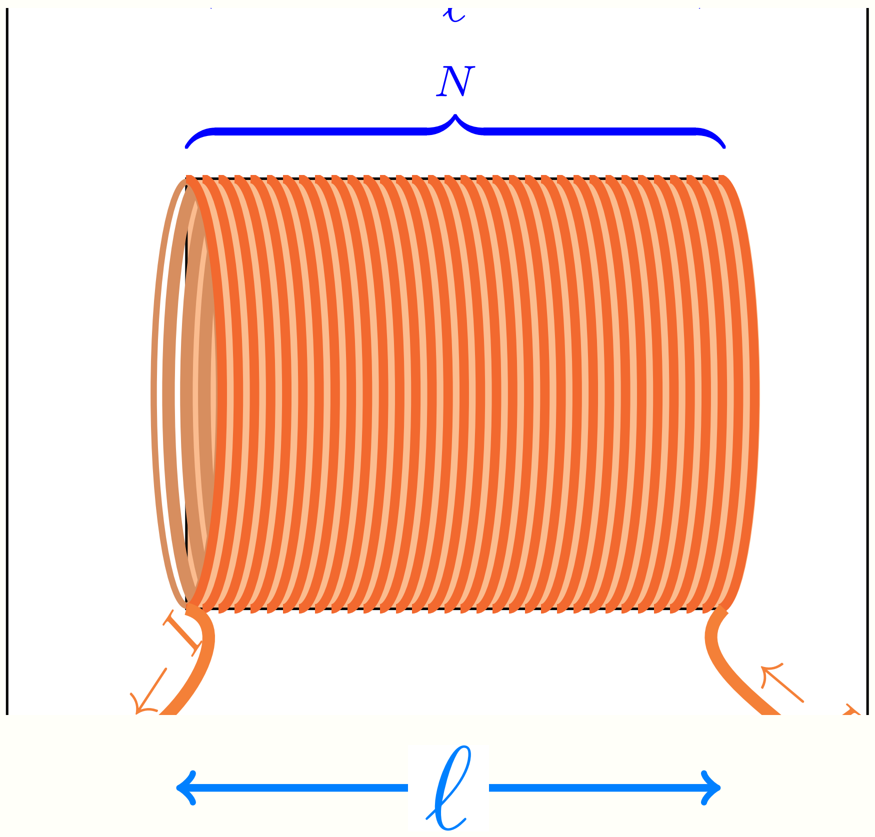
$$U_B = L\frac{I^2}{2}$$

$$L = \mu_0 \frac{N^2}{\ell} A$$



# Equações de Maxwell
# Energia da radiação

$U_B = ?$




$$U = U_E + U_B$$

$$U_B = L\frac{I^2}{2}$$

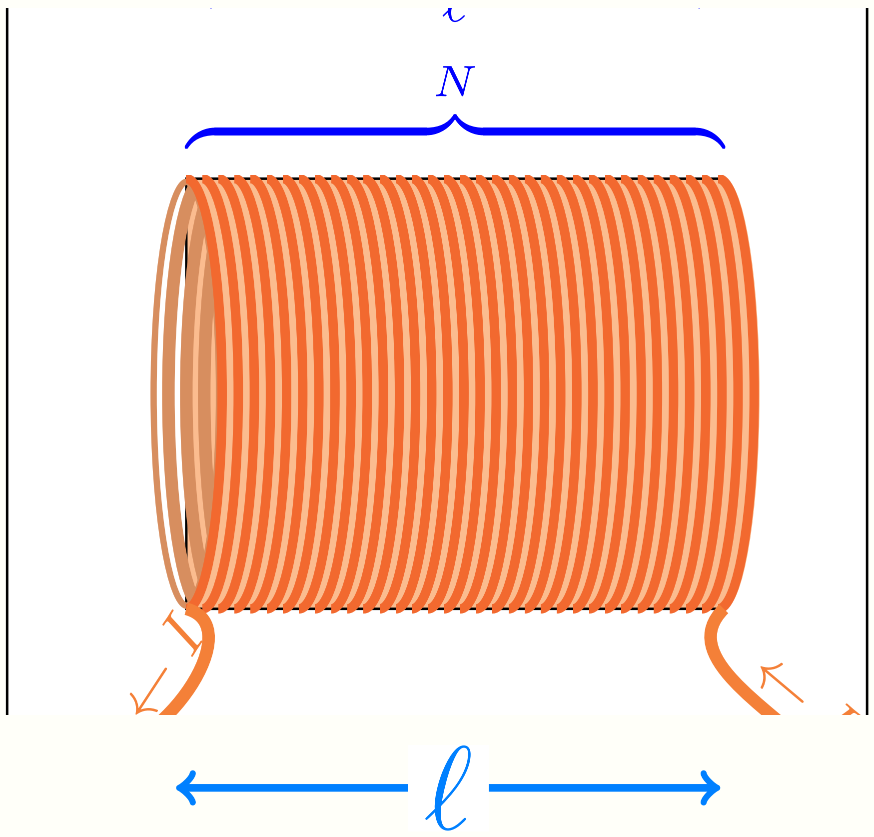
$$L = \mu_0 \frac{N^2}{\ell} A$$

$$U_L = \mu_0 \frac{N^2}{\ell} A \frac{I^2}{2}$$

# Equações de Maxwell
# Energia da radiação

$U_B = ?$

$U_B = \mu_0 \frac{N^2}{\ell} A \frac{I^2}{2}$




$$U = U_E + U_B$$

$$U_B = L\frac{I^2}{2}$$

$$L = \mu_0 \frac{N^2}{\ell} A$$

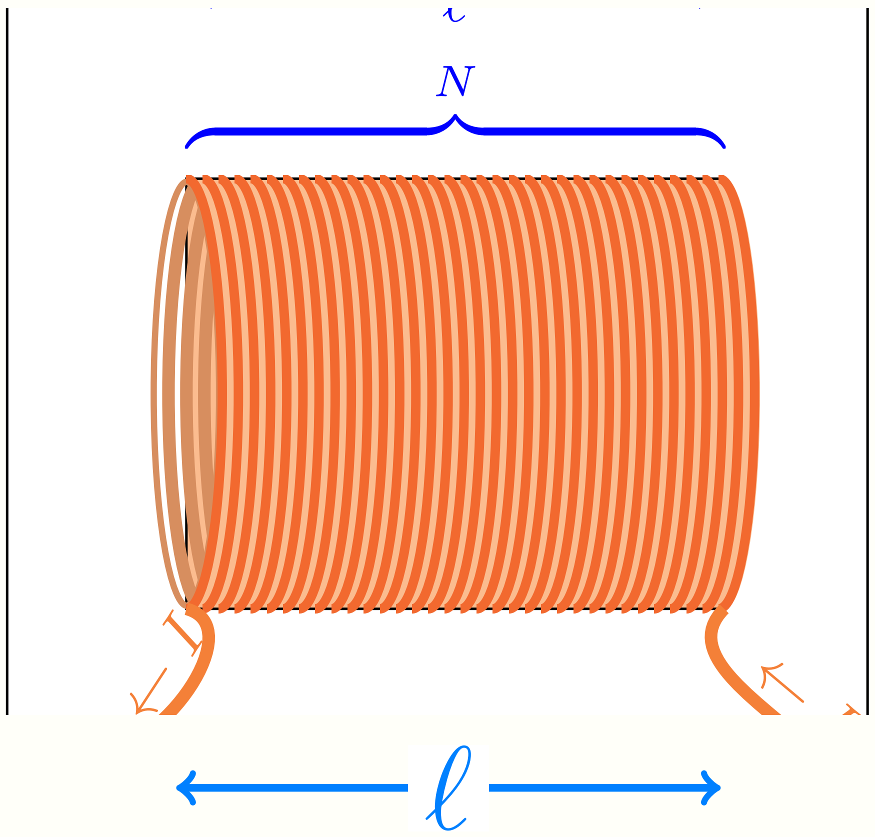
$$U_B = \mu_0 \frac{N^2}{\ell} A \frac{I^2}{2}$$

# Equações de Maxwell
# Energia da radiação

$U_B = ?$

$U_B = \mu_0 \frac{N^2}{\ell} A \frac{I^2}{2}$

$$U = U_E + U_B$$



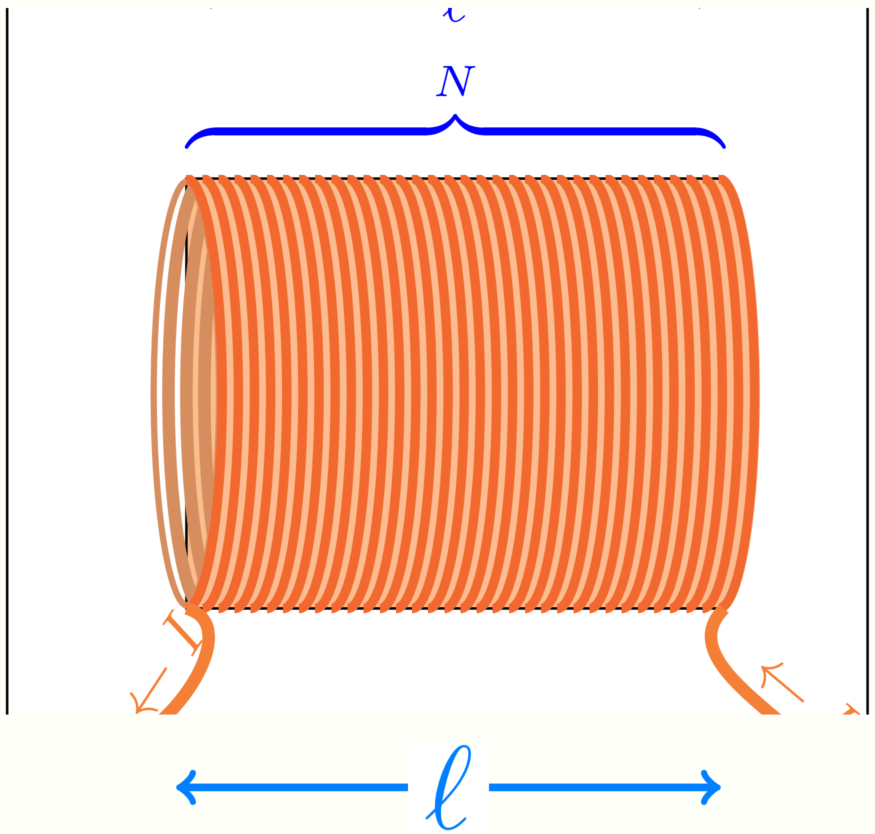
# Equações de Maxwell
# Energia da radiação

$U_B = ?$

$U_B = \mu_0 \frac{N^2}{\ell} A \frac{I^2}{2}$

$$U = U_E + U_B$$

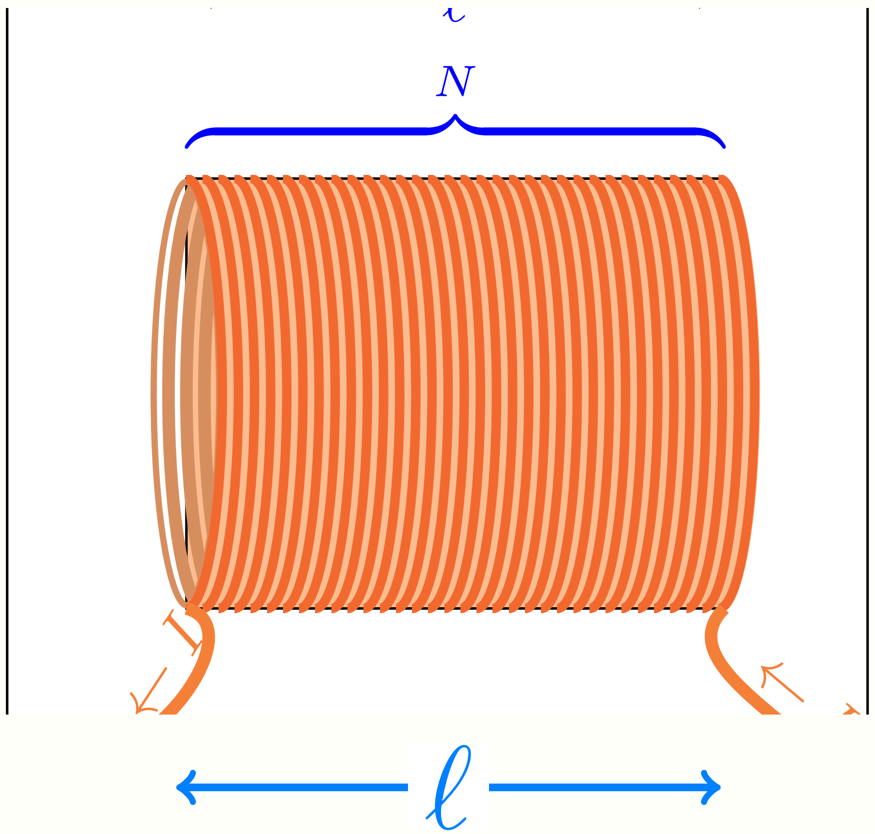
$$B = \mu_0 \frac{N}{\ell} I$$



# Equações de Maxwell
# Energia da radiação

$U_B = ?$

$U_B = \mu_0 \frac{N^2}{\ell} A \frac{I^2}{2}$



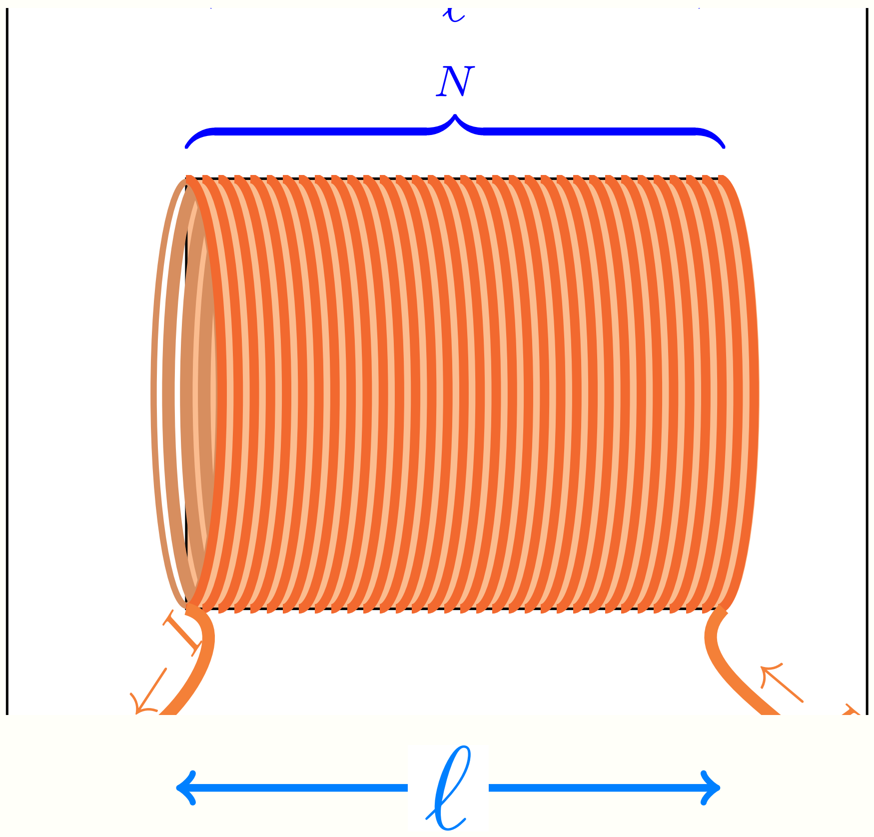

$$U = U_E + U_B$$

$$B = \mu_0 \frac{N}{\ell} I$$

$$U_B = \mu_0 \frac{N^2}{\ell^2} \ell A \frac{I^2}{2}$$

# Equações de Maxwell
# Energia da radiação

$$u_B = \frac{B^2}{2\mu_0}$$




$$U = U_E + U_B$$

$$B = \mu_0 \frac{N}{\ell} I$$

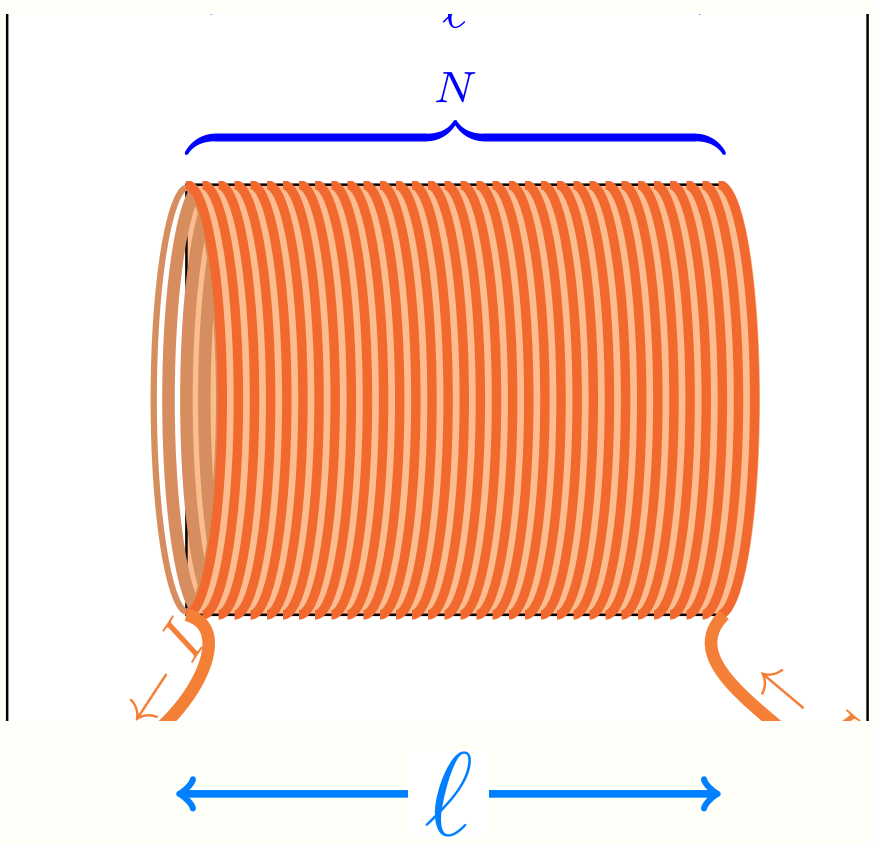
$$U_B = \mu_0 \frac{N^2}{\ell^2} \ell A \frac{I^2}{2}$$

$$U_B = \frac{B^2}{2\mu_0} \ell A$$

# Equações de Maxwell
# Energia da radiação

$U_B = ?$

$U_B = \mu_0 \frac{N^2}{\ell} A \frac{I^2}{2}$




$$U = U_E + U_B$$

$$B = \mu_0 \frac{N}{\ell} I$$

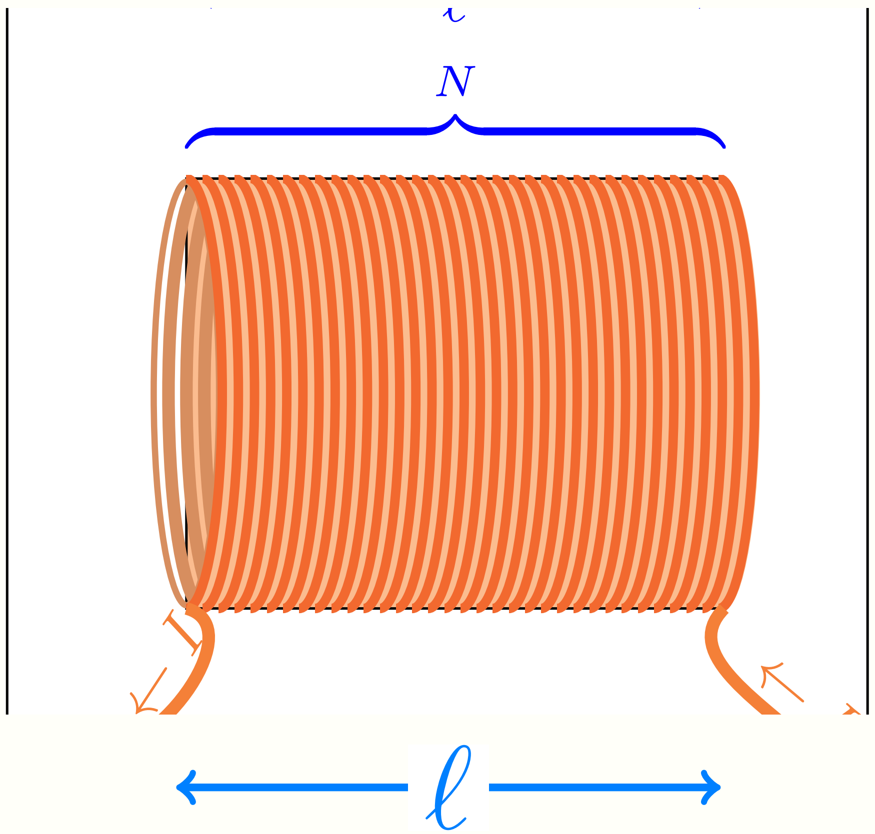
$$U_B = \mu_0 \frac{N^2}{\ell^2} \ell A \frac{I^2}{2}$$

$$U_B = \frac{B^2}{2\mu_0} \ell A \quad \Rightarrow \quad \frac{U_B}{\mathscr{V}} = \frac{B^2}{2\mu_0}$$

# Equações de Maxwell
# Energia da radiação

$U_B = ?$

$U_B = \mu_0 \frac{N^2}{\ell} A \frac{I^2}{2}$




$$U = U_E + U_B$$

$$B = \mu_0 \frac{N}{\ell} I$$

$$U_B = \mu_0 \frac{N^2}{\ell^2} \ell A \frac{I^2}{2}$$

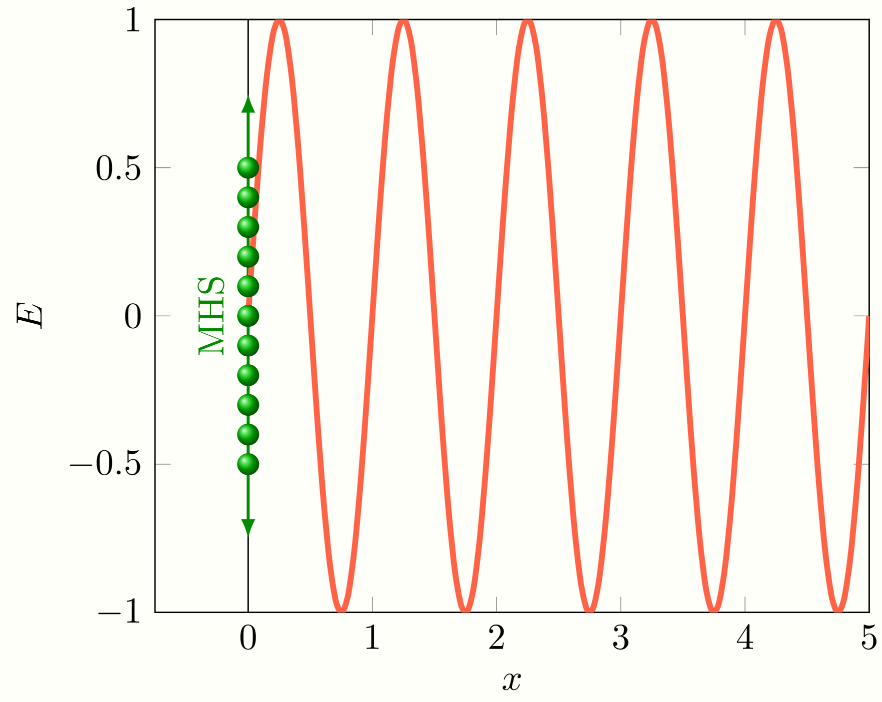
$$U_B = \frac{B^2}{2\mu_0} \ell A$$

$$u_B = \frac{B^2}{2\mu_0}$$

# Equações de Maxwell
# Energia da radiação

$$U = U_E + U_B$$

$$u_B = \frac{B^2}{2\mu_0}$$

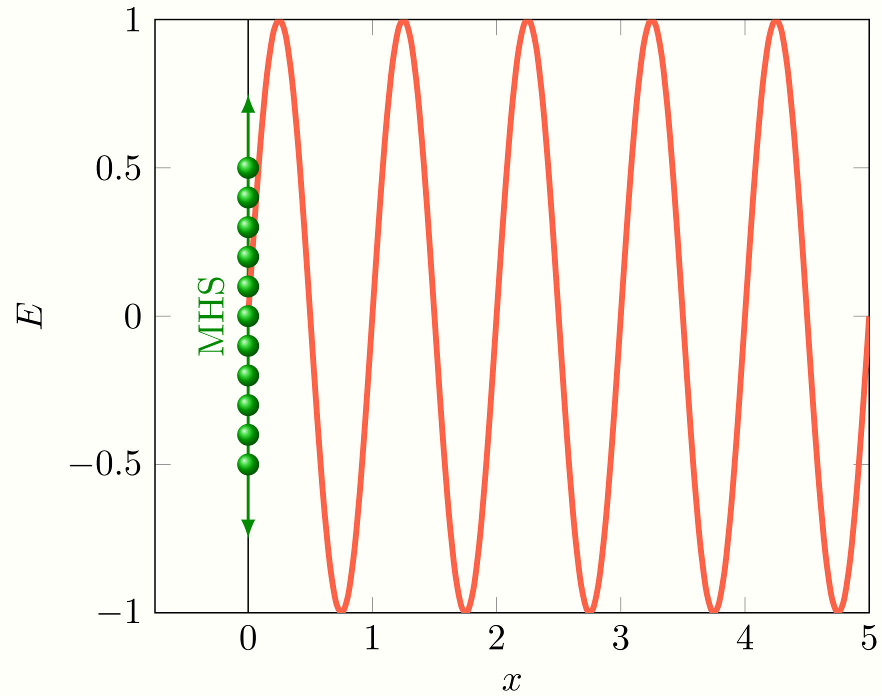


# Equações de Maxwell
# Energia da radiação

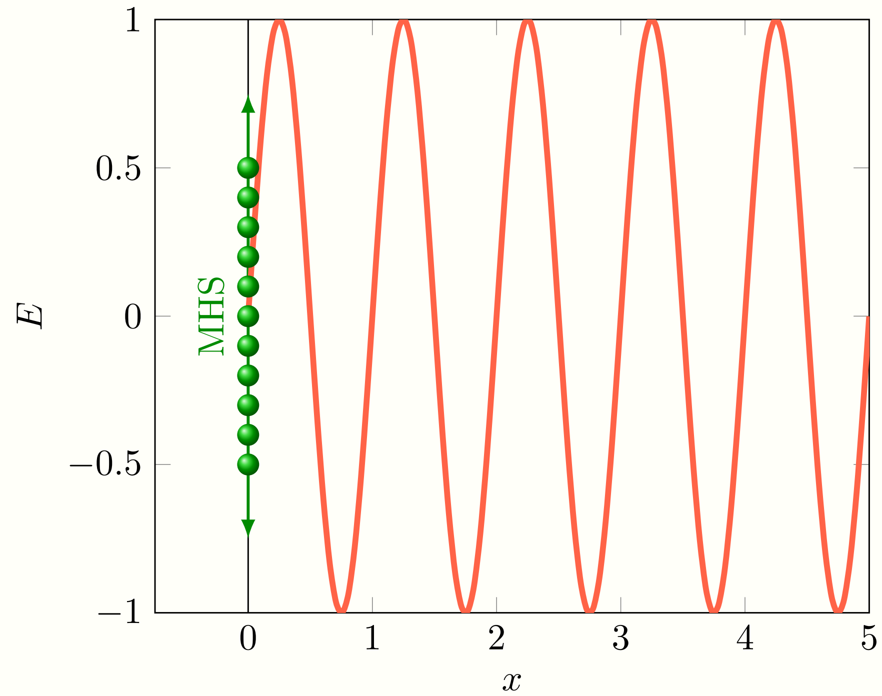
$$U = U_E + U_B$$

$$u_B = \frac{B^2}{2\mu_0}$$

$$u_E = \epsilon_0 \frac{E^2}{2}$$



# Equações de Maxwell
# Energia da radiação




$$U = U_E + U_B$$

$$u_B = \frac{B^2}{2\mu_0}$$

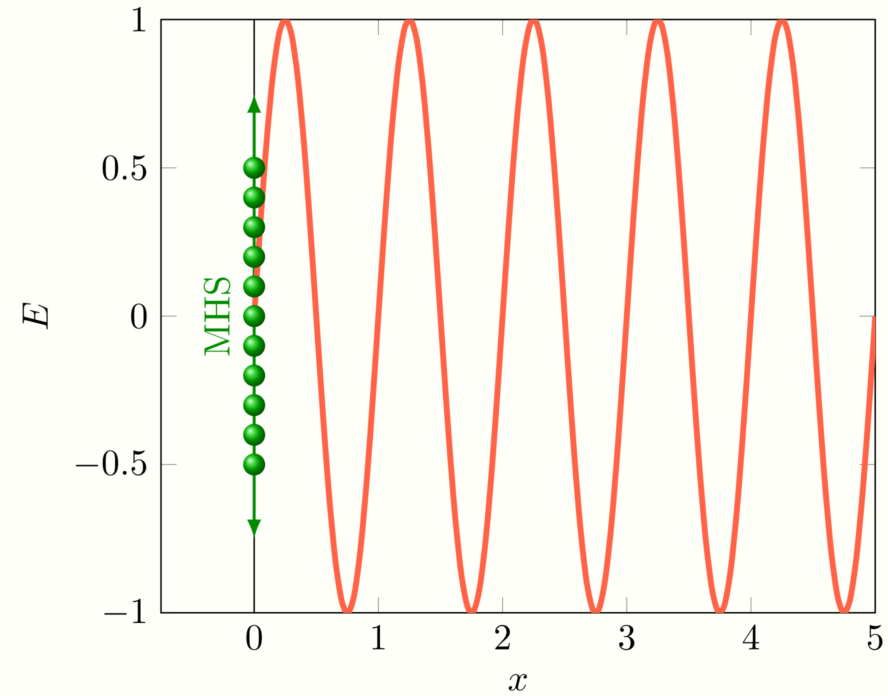
$$u_E = \epsilon_0 \frac{E^2}{2}$$

$$u = \epsilon_0 \frac{E^2}{2} + \frac{B^2}{2\mu_0}$$

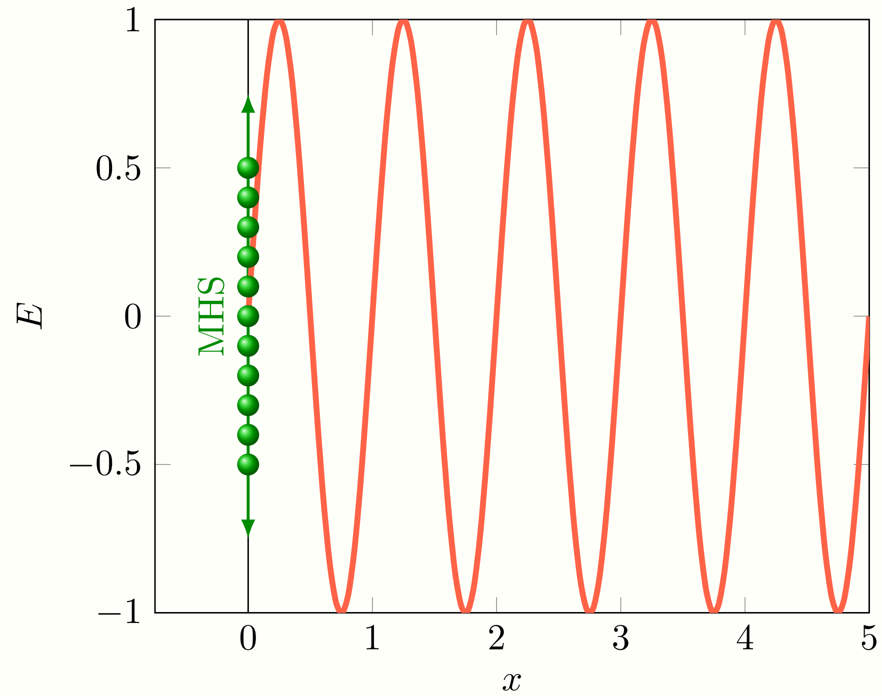
# Equações de Maxwell
# Energia da radiação

$$U = U_E + U_B$$

$$u(\vec{r}, t) = \epsilon_0 \frac{E^2}{2} + \frac{B^2}{2\mu_0}$$



# Equações de Maxwell
# Energia da radiação




$$U = U_E + U_B$$

$$u(\vec{r}, t) = \epsilon_0 \frac{E^2}{2} + \frac{B^2}{2\mu_0}$$

$$\frac{\partial u}{\partial t} = \epsilon_0 \vec{E} \cdot \frac{\partial \vec{E}}{\partial t} + \frac{1}{\mu_0} \vec{B} \cdot \frac{\partial \vec{B}}{\partial t}$$

# Equações de Maxwell
# Espaço livre

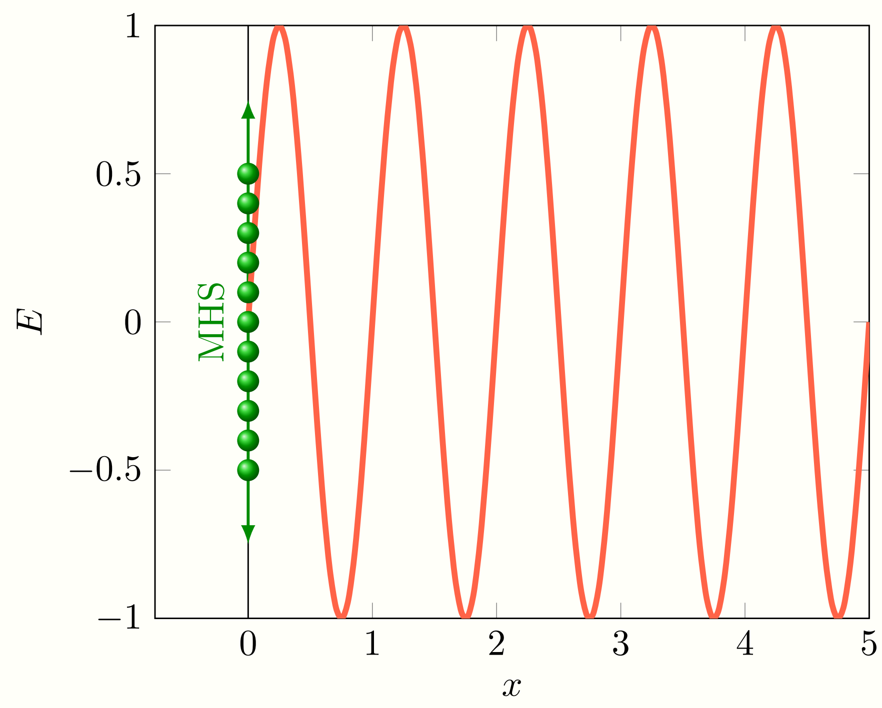
$$\vec{\nabla} \cdot \vec{E} = 0$$

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

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

$$\vec{\nabla} \times \vec{B} = \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

# Equações de Maxwell
# Energia da radiação



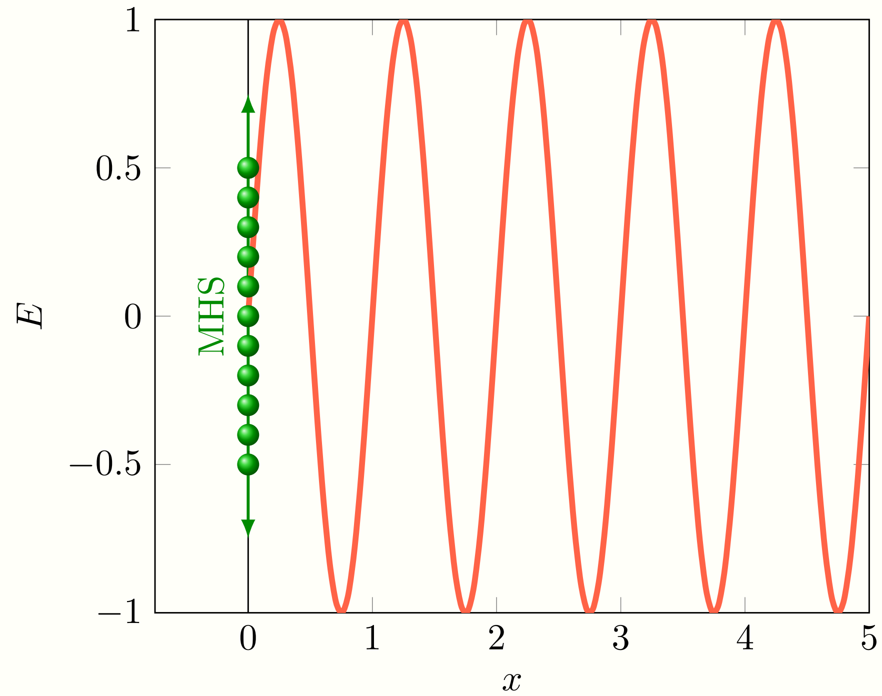

$$U = U_E + U_B$$

$$u(\vec{r}, t) = \epsilon_0 \frac{E^2}{2} + \frac{B^2}{2\mu_0}$$

$$\frac{\partial u}{\partial t} = \epsilon_0 \vec{E} \cdot \frac{\partial \vec{E}}{\partial t} + \frac{1}{\mu_0} \vec{B} \cdot \frac{\partial \vec{B}}{\partial t}$$

$$\frac{\partial u}{\partial t} = \frac{1}{\mu_0} \left( \vec{E} \cdot \vec{\nabla} \times \vec{B} - \vec{B} \cdot \vec{\nabla} \times \vec{E} \right)$$

# Equações de Maxwell
# Energia da radiação




$$U = U_E + U_B$$

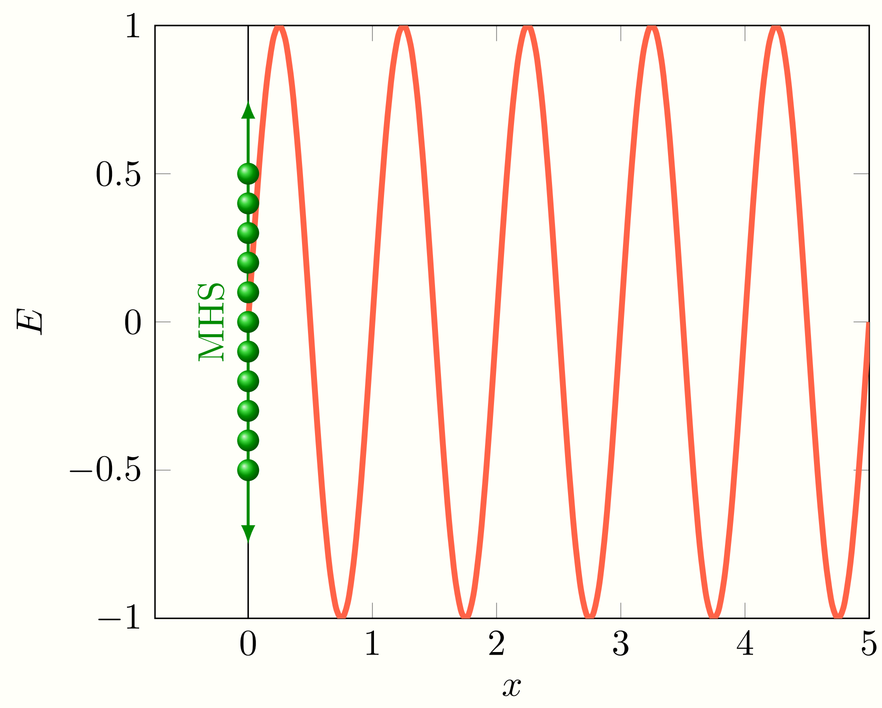
$$u(\vec{r}, t) = \epsilon_0 \frac{E^2}{2} + \frac{B^2}{2\mu_0}$$

$$\frac{\partial u}{\partial t} = \epsilon_0 \vec{E} \cdot \frac{\partial \vec{E}}{\partial t} + \frac{1}{\mu_0} \vec{B} \cdot \frac{\partial \vec{B}}{\partial t}$$

$$\frac{\partial u}{\partial t} = \frac{1}{\mu_0}\left(\vec{E} \cdot \vec{\nabla} \times \vec{B} - \vec{B} \cdot \vec{\nabla} \times \vec{E}\right) = -\frac{1}{\mu_0} \vec{\nabla} \cdot \vec{E} \times \vec{B}$$

# Equações de Maxwell
# Energia da radiação

$$\frac{\partial u}{\partial t} = -\frac{1}{\mu_0}\vec{\nabla}\cdot\vec{E}\times\vec{B}$$




$$\vec{S} \equiv \frac{1}{\mu_0}\vec{E}\times\vec{B}$$ (Poynting)

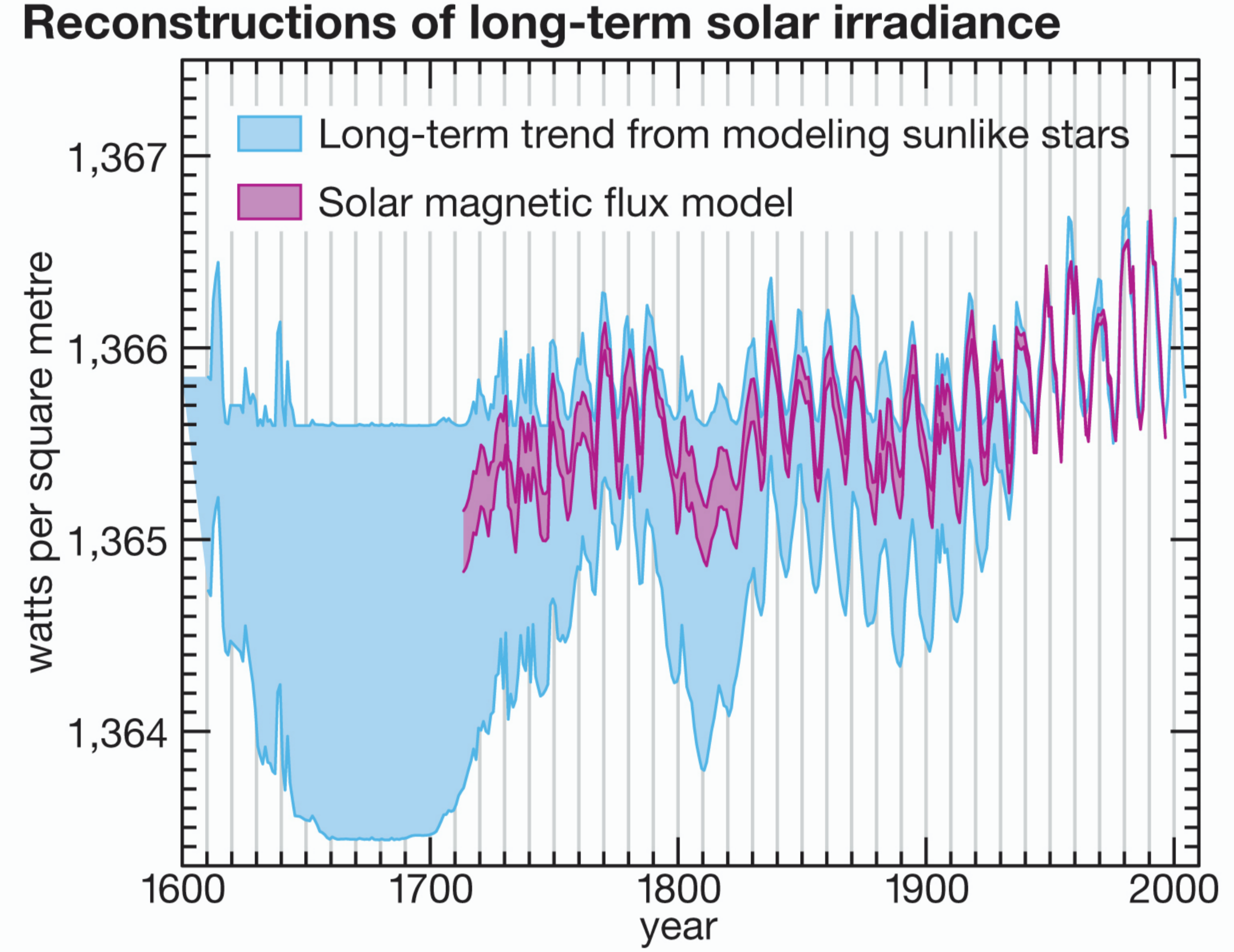
$$\frac{\partial u}{\partial t} + \vec{\nabla}\cdot\vec{S} = 0$$

$$\frac{\partial u}{\partial t} + \vec{\nabla} \cdot \vec{S} = 0$$

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$

# Pratique o que aprendeu

## Campo elétrico num raio de sol




Source: Climate Change 2007: The Physical Science Basis, Summary for Policymakers, Intergovernmental Panel on Climate Change

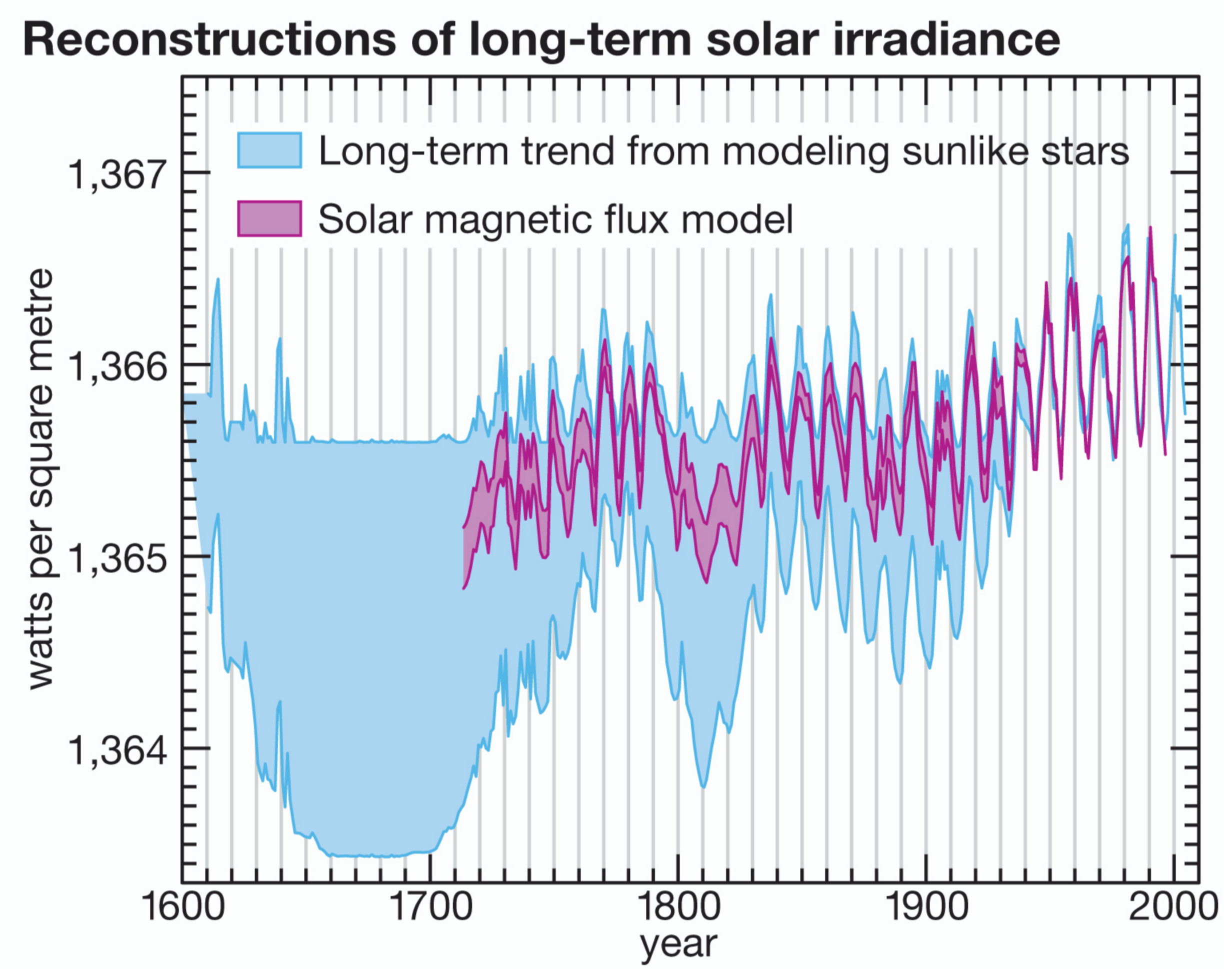
$$\frac{\partial u}{\partial t} + \vec{\nabla} \cdot \vec{S} = 0$$

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$

# Pratique o que aprendeu

## Campo elétrico num raio de sol

$$[S] = [u]\frac{L}{T}$$




Source: Climate Change 2007: The Physical Science Basis, Summary for Policymakers, Intergovernmental Panel on Climate Change

$$\frac{\partial u}{\partial t} + \vec{\nabla} \cdot \vec{S} = 0$$

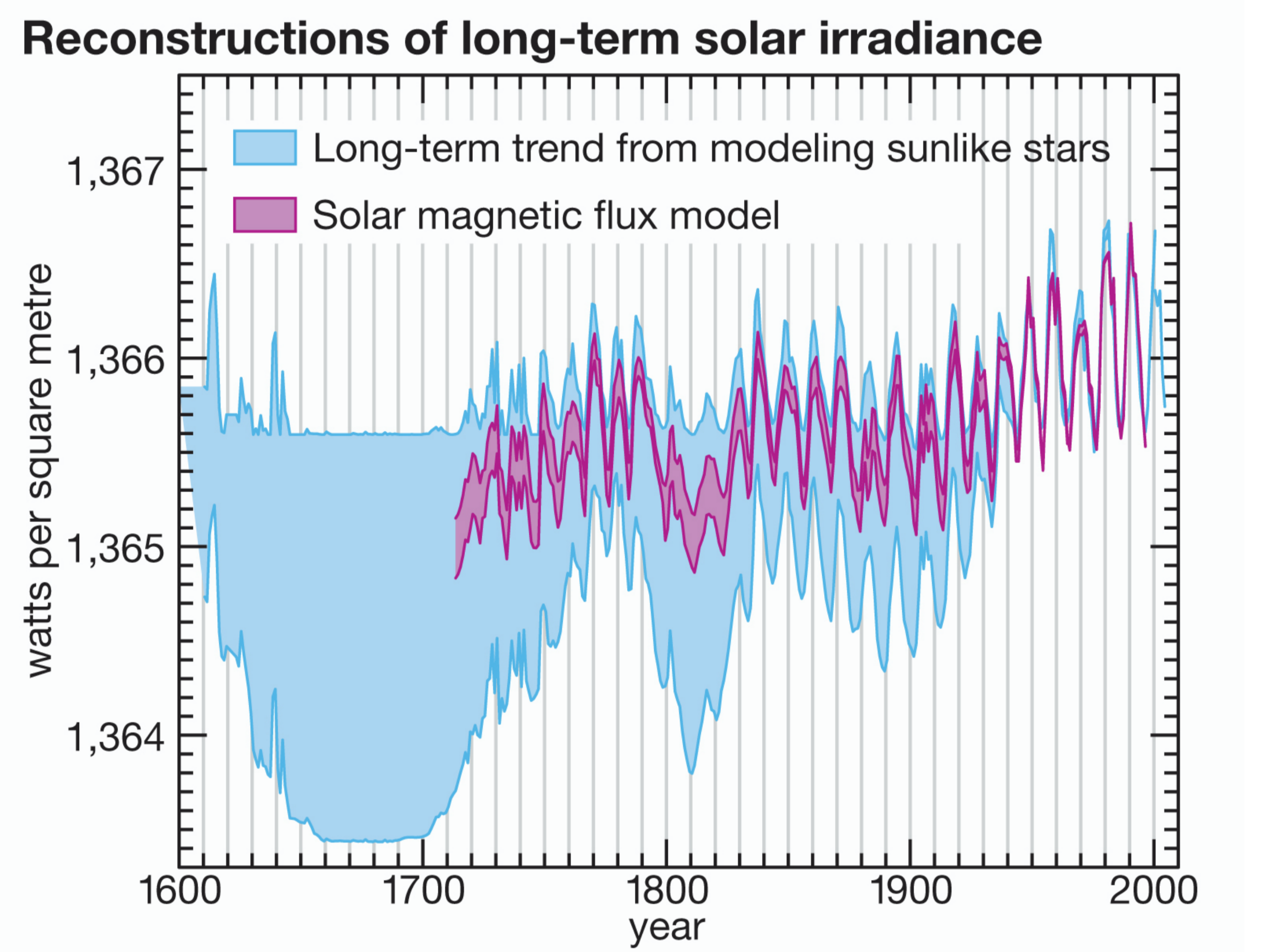
# Pratique o que aprendeu

## Campo elétrico num raio de sol

$$\overrightarrow{S} = \frac{1}{\mu_0} \overrightarrow{E} \times \overrightarrow{B}$$

$$[S] = [u]\frac{L}{T}$$

$$[S] = [U]\frac{L}{L^3 T}$$




Source: Climate Change 2007: The Physical Science Basis, Summary for Policymakers, Intergovernmental Panel on Climate Change

$$\frac{\partial u}{\partial t} + \vec{\nabla} \cdot \vec{S} = 0$$

# Pratique o que aprendeu

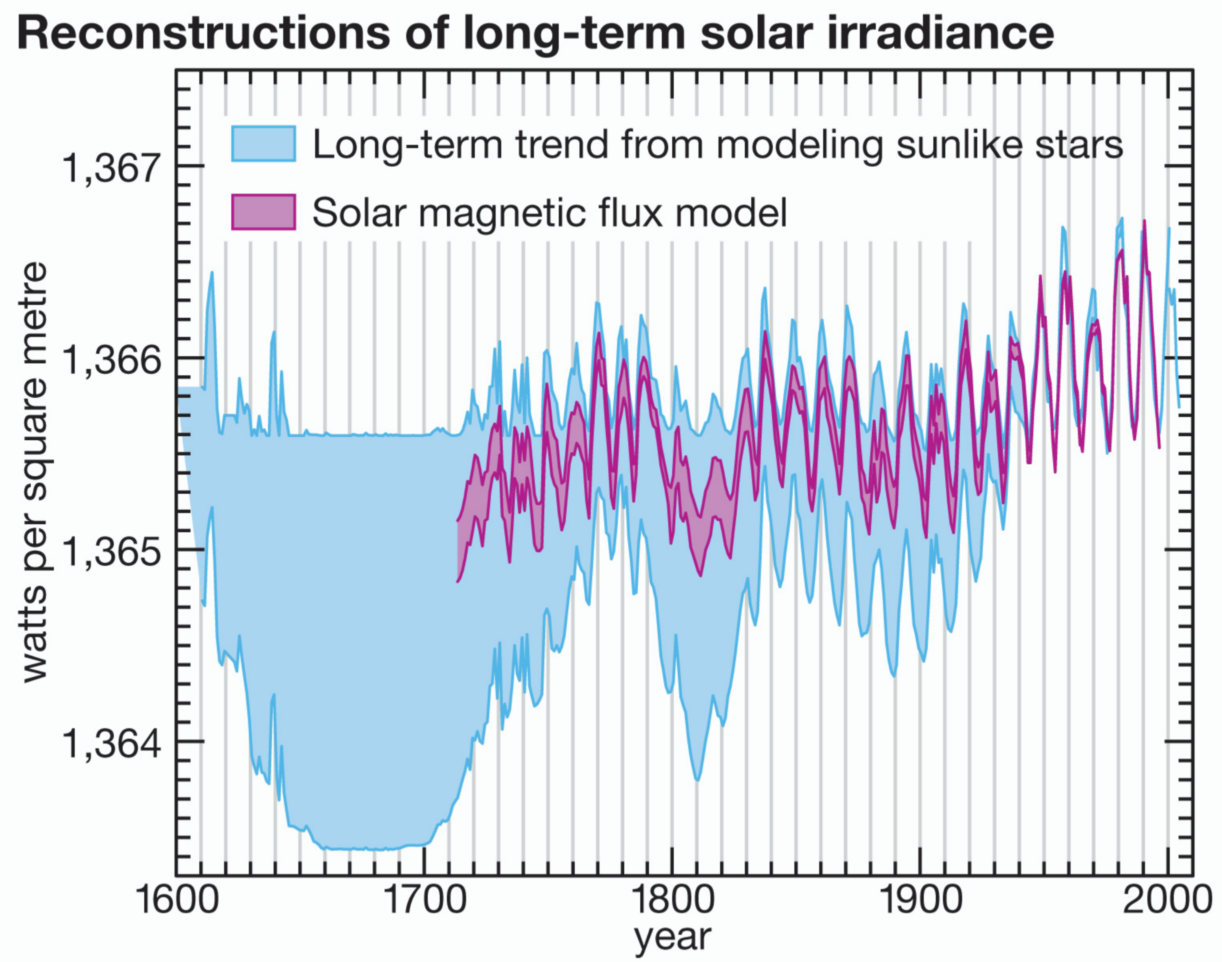
$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$

## Campo elétrico num raio de sol

$$[S] = [u]\frac{L}{T}$$

$$[S] = [U]\frac{L}{L^3 T}$$

$$[S] = \frac{[\text{Potência}]}{L^2}$$




Source: Climate Change 2007: The Physical Science Basis, Summary for Policymakers, Intergovernmental Panel on Climate Change

$$\frac{\partial u}{\partial t} + \vec{\nabla} \cdot \vec{S} = 0$$

# Pratique o que aprendeu

## Campo elétrico num raio de sol

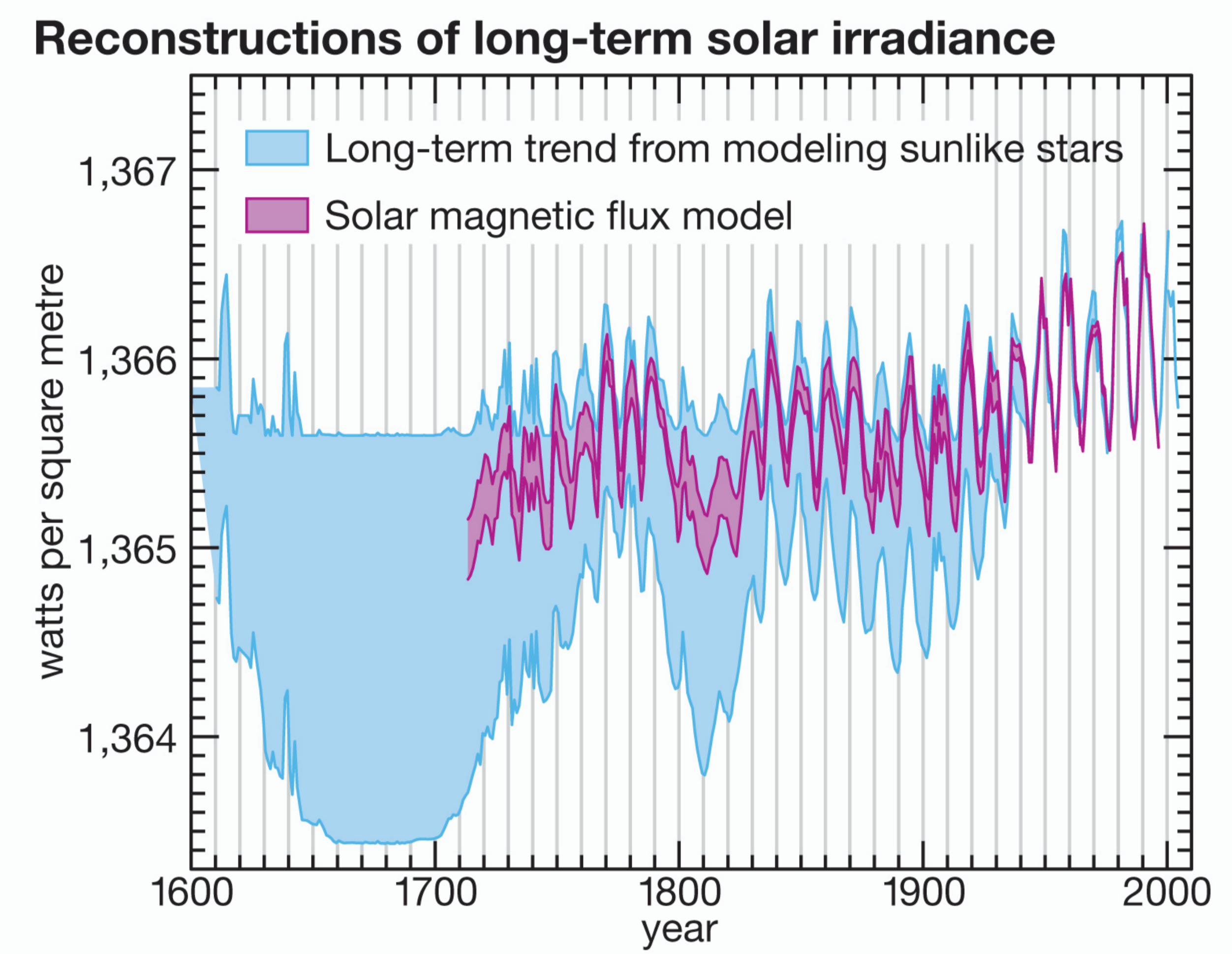
$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$

$$[S] = [u]\frac{L}{T}$$

$$[S] = [U]\frac{L}{L^3 T}$$

$$[S] = \frac{[\text{Potência}]}{L^2}$$

$$S = 1.37 \times 10^3\,\mathrm{W/m^2}$$




Source: Climate Change 2007: The Physical Science Basis, Summary for Policymakers, Intergovernmental Panel on Climate Change

$$\frac{\partial u}{\partial t} + \vec{\nabla} \cdot \vec{S} = 0$$

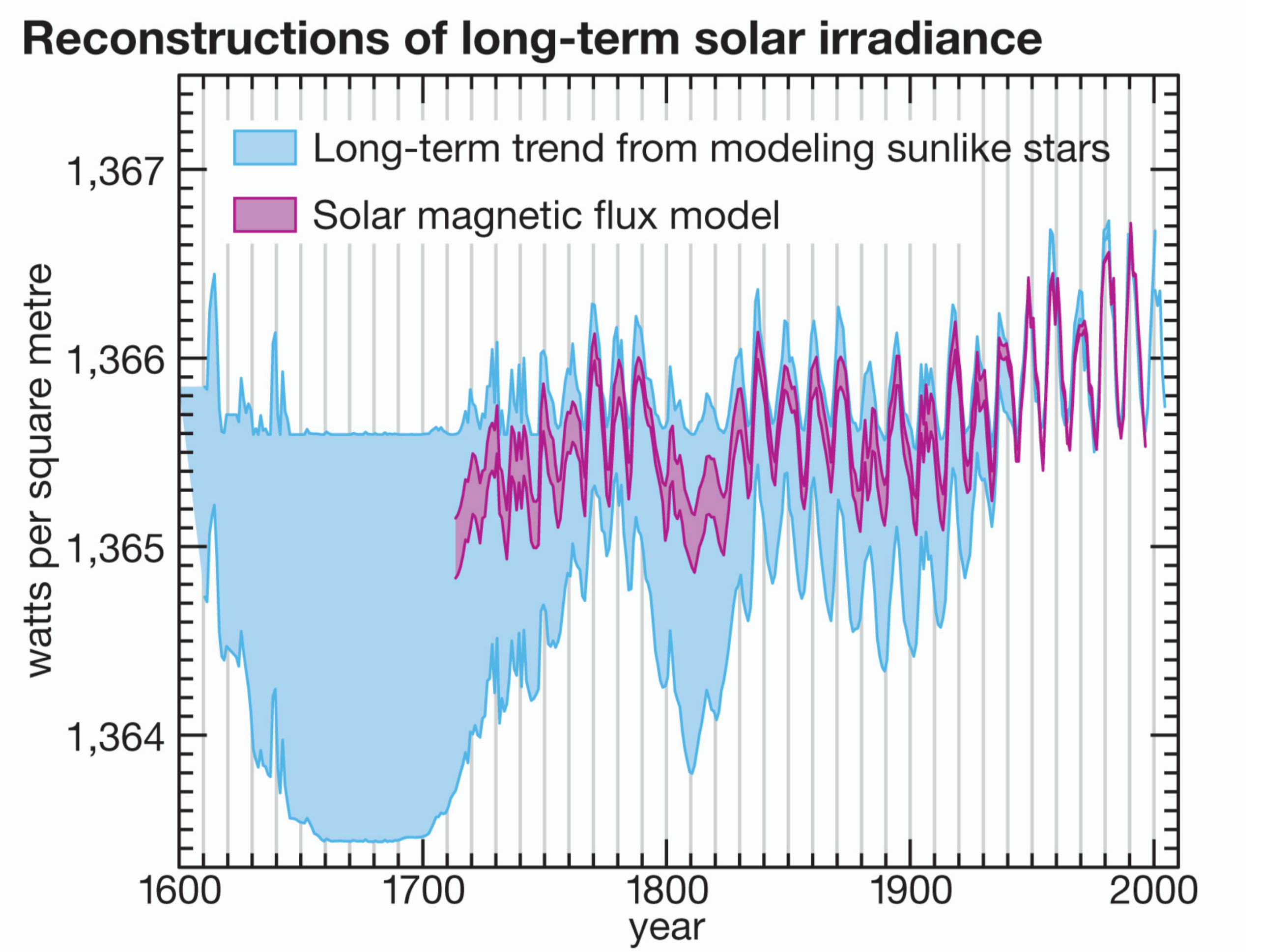
$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$

# Pratique o que aprendeu

## Campo elétrico num raio de sol

$$S = 1.37 \times 10^3 \, \mathrm{W/m^2}$$

$$S = \frac{EB}{\mu_0}$$




Source: Climate Change 2007: The Physical Science Basis, Summary for Policymakers, Intergovernmental Panel on Climate Change

$$\frac{\partial u}{\partial t} + \vec{\nabla} \cdot \vec{S} = 0$$

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$

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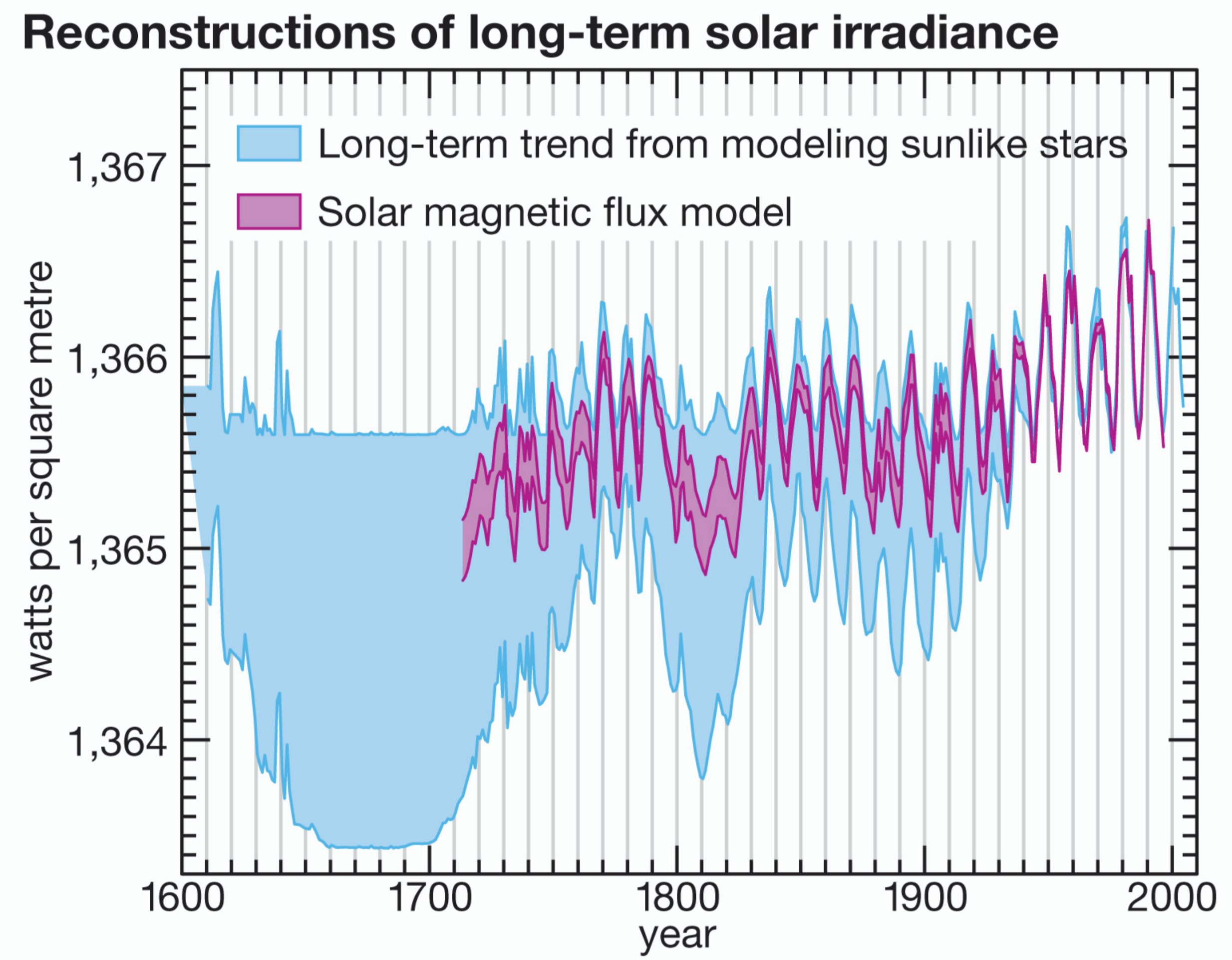


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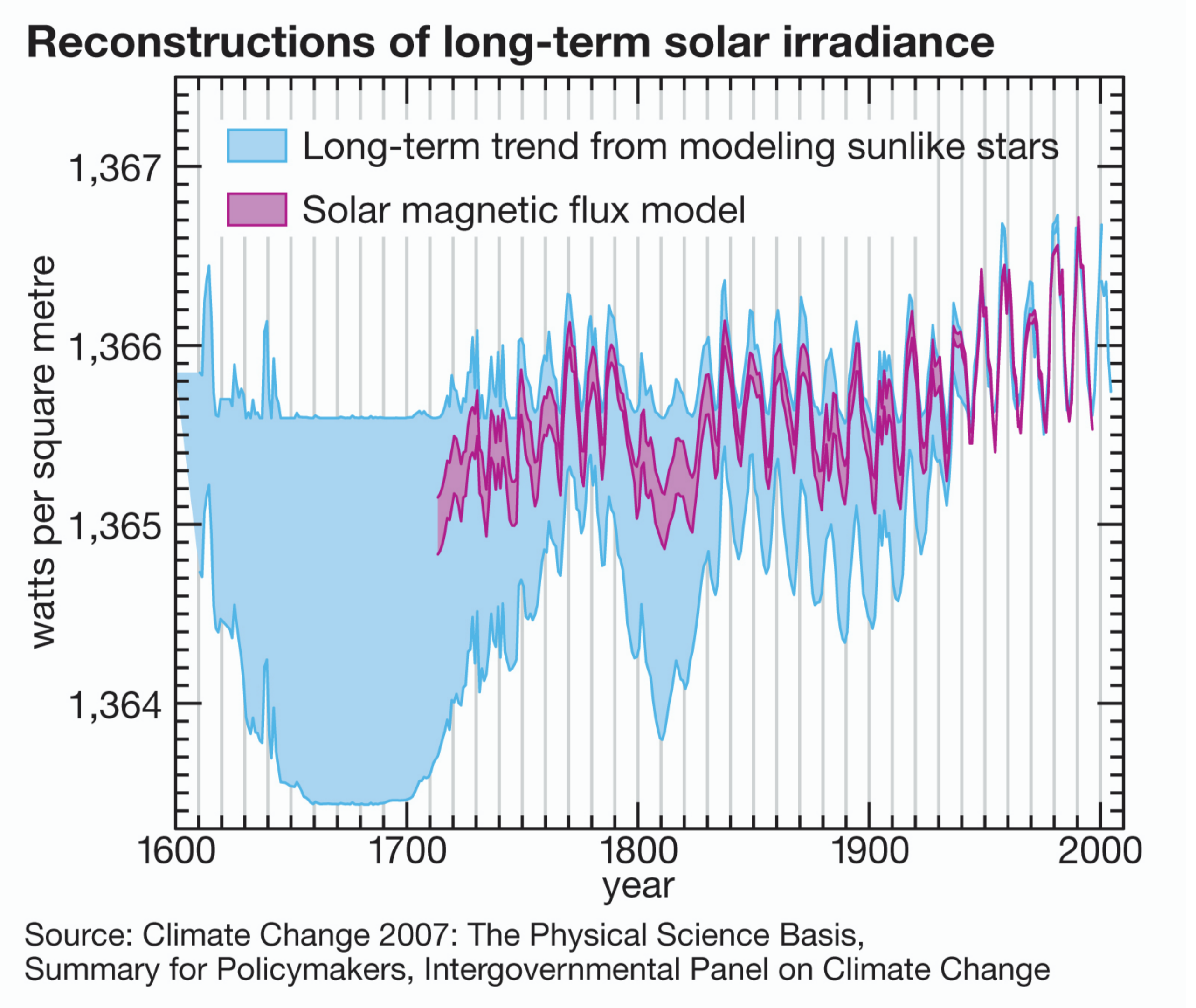
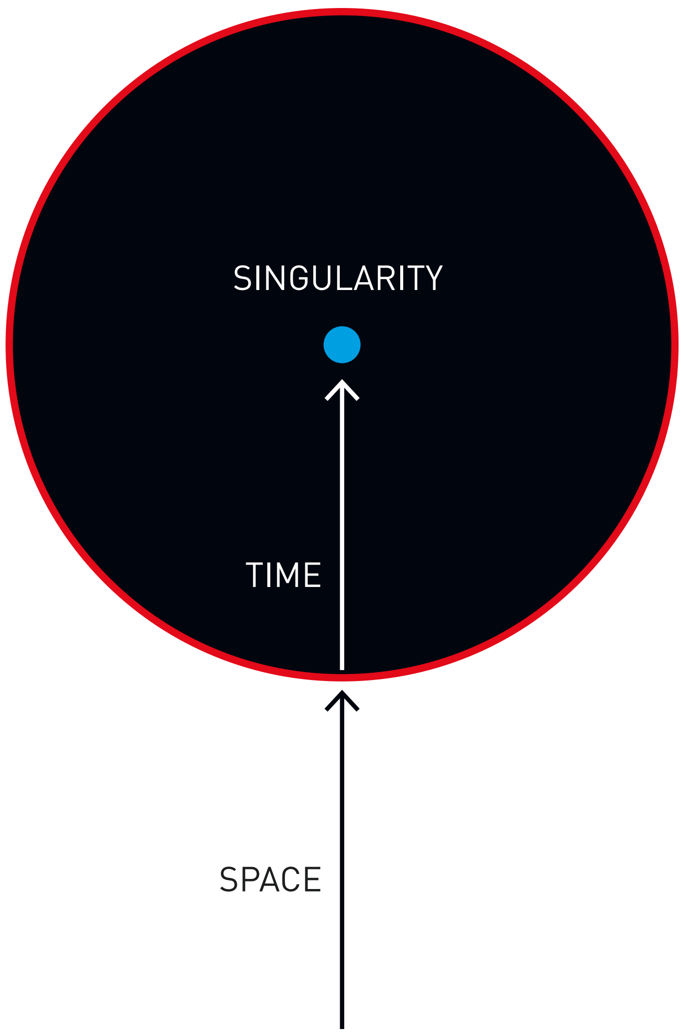



$$S = \frac{EB}{\mu_0} \qquad B = \frac{E}{c}$$

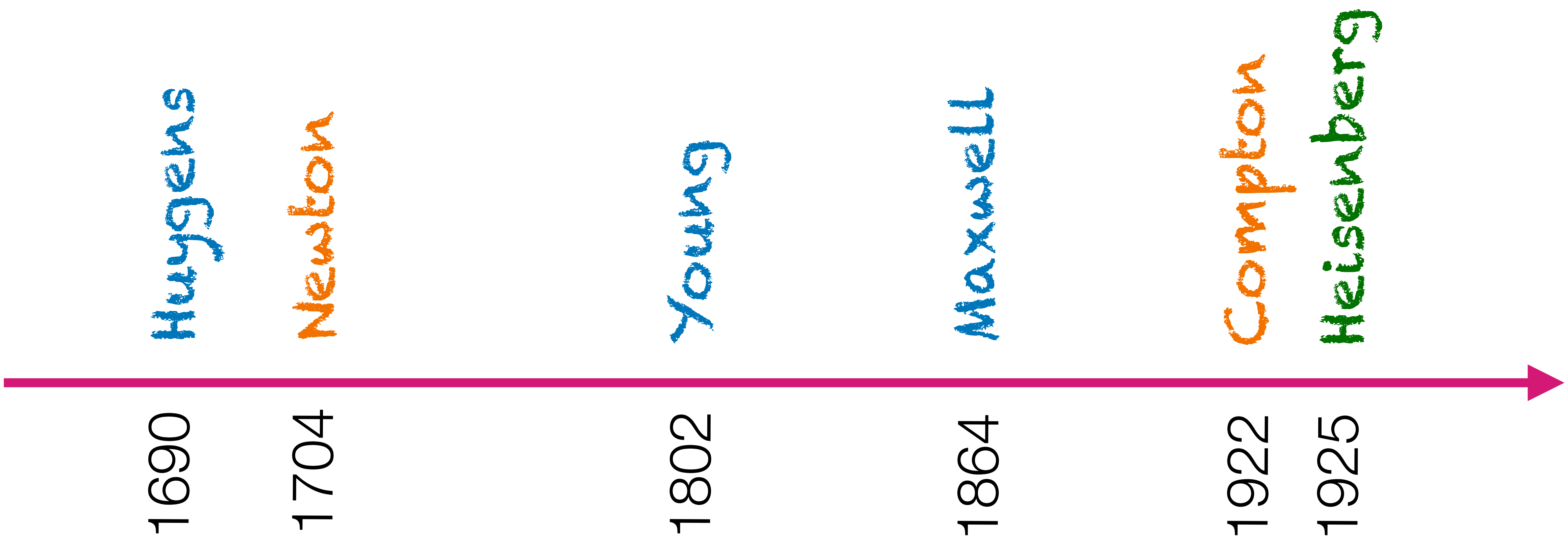
$$\langle S \rangle = \frac{1}{2} \frac{E^2}{\mu_0 c}$$

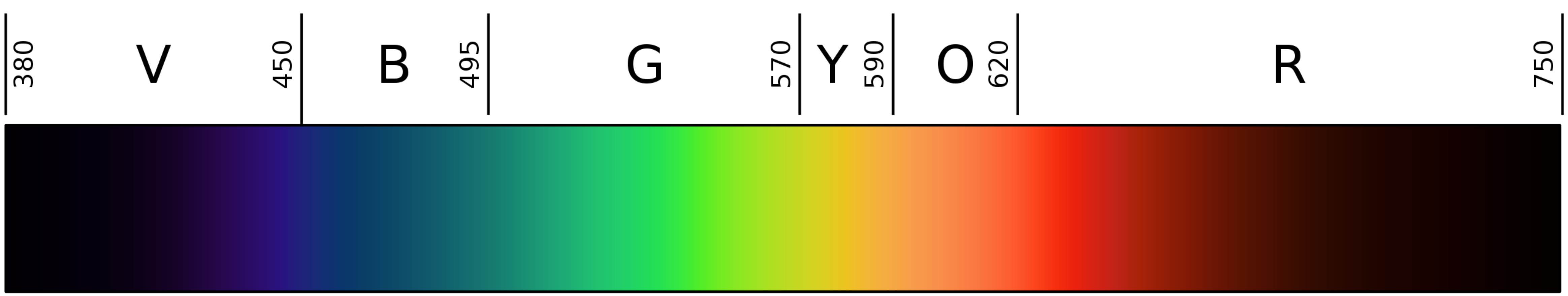
$$E = \sqrt{2 \times 1.37 \times 10^3 4\pi \times 10^{-7} 3 \times 10^8} = 1.02 \frac{\mathrm{kV}}{\mathrm{m}}$$

# Prêmio Nobel de Física 2020




# Luz


Huygens
1690
Newton
1704
Young
1802
Maxwell
1864
Compton
1922
Heisenberg
1925


380
V
450
B
495
G
570
Y
590
O
620
R
750