

Eletromagnetismo

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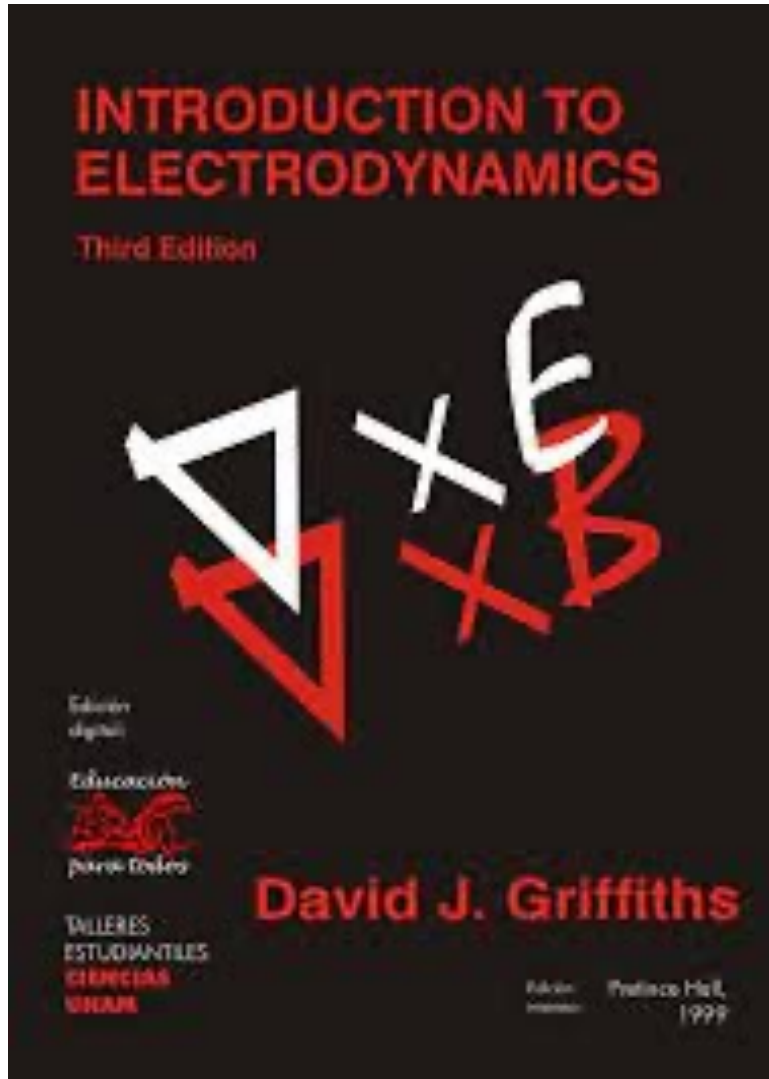
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Plano do Curso

16/08	13/09	11/10	08/11
19/08	16/09	14/10	11/11
23/08	20/09 P1	18/10	15/11
26/08	23/09	21/10 P2	18/11
30/08	27/09 ←	25/10	22/11
02/09	30/09	28/10	25/11
06/09	04/10	01/11	29/11 P3
09/09	07/10	04/11	02/12 ex
			06/12 Sub

Bibliografia



Capítulo 2 : eletrostática

Capítulo 5 : magnetostática

Capítulo 7 : eletrodinâmica

Capítulo 8 : leis de conservação

Capítulo 9 : ondas eletromagnéticas

Capítulo 10 : campos e potenciais

Capítulo 11 : radiação

Bibliografia

Física 3

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Suzana Salem Vasconcelos

Instituto de Física da Universidade de São Paulo

São Paulo, 5 de fevereiro de 2020

Aula 9

Campo magnético vem de
cargas elétricas em movimento !



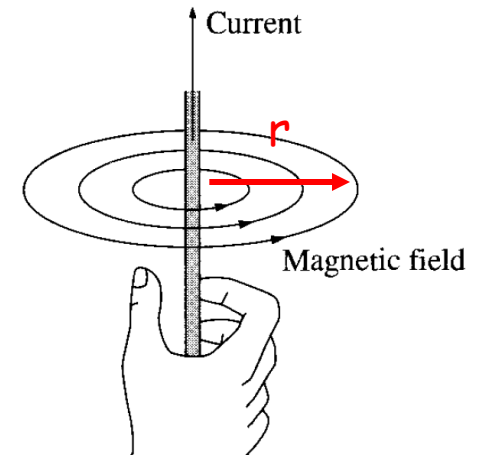
Andre-Marie Ampère

Lei de Ampère

A corrente no fio gera campo magnético :

Usando Biot-Savart:

$$B = \frac{\mu_0 I}{2 \pi r}$$



Vamos calcular :

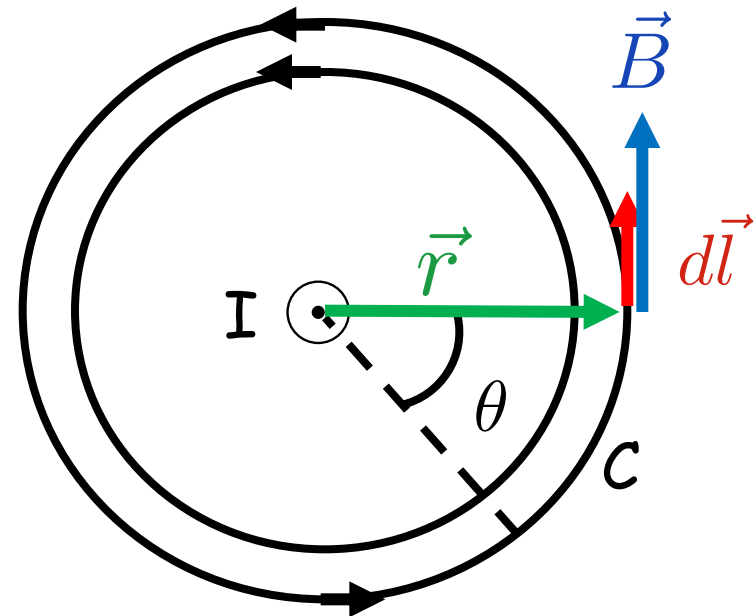
$$\oint_C \vec{B} \cdot d\vec{l} \quad \vec{B} \cdot d\vec{l} = B dl = B r d\theta$$

$$\oint_C \vec{B} \cdot d\vec{l} = B r \int_0^{2\pi} d\theta = B r 2\pi$$

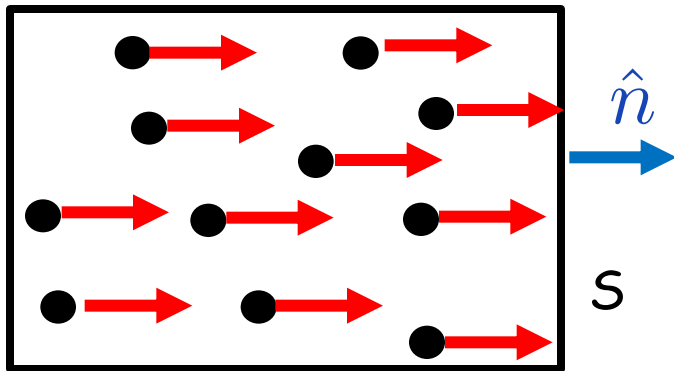
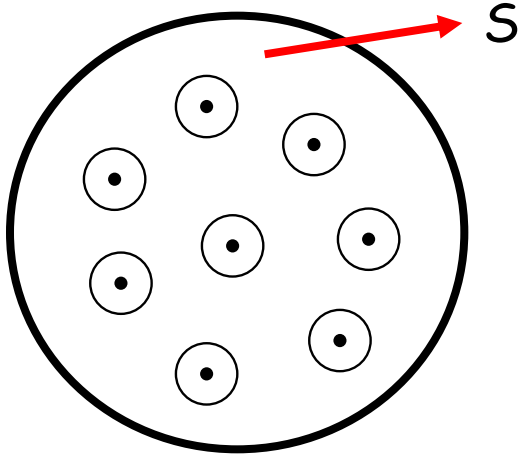
$$\oint_C \vec{B} \cdot d\vec{l} = \frac{\mu_0 I}{2\pi r} \cancel{2\pi r}$$

$$\oint_C \vec{B} \cdot d\vec{l} = \mu_0 I$$

corrente
enlaçada em C



Fio com seção transversal grande = tubo de correntes



Densidade de corrente : $J = \frac{\text{corrente}}{\text{área}}$

$$J = \frac{dI}{da}$$

$$\vec{J} = \frac{d\vec{I}}{da}$$

$$d\vec{I} = \vec{J} da$$

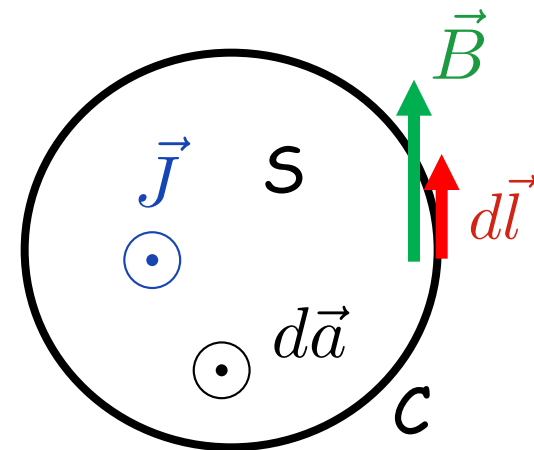
$$d\vec{I} \cdot \hat{n} = \vec{J} \cdot \hat{n} da$$

$$dI = \vec{J} \cdot d\vec{a}$$

$$I = \int_S \vec{J} \cdot d\vec{a}$$

Teorema de Stokes

$$\oint_C \vec{B} \cdot d\vec{l} = \mu_0 I$$



$$\oint_C \vec{B} \cdot d\vec{l} = \int_S (\vec{\nabla} \times \vec{B}) \cdot d\vec{a}$$

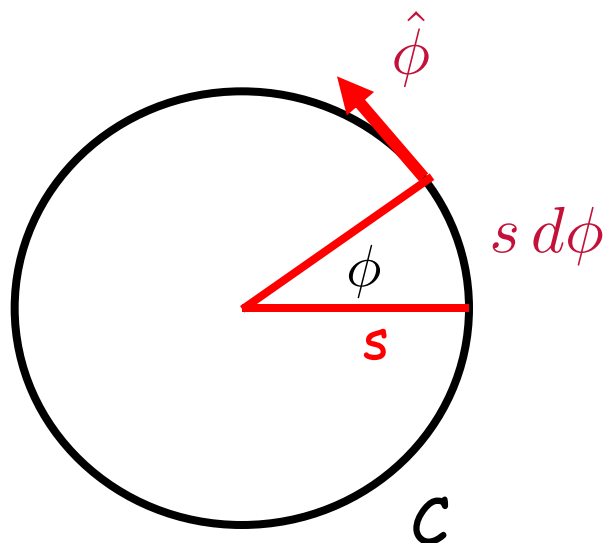
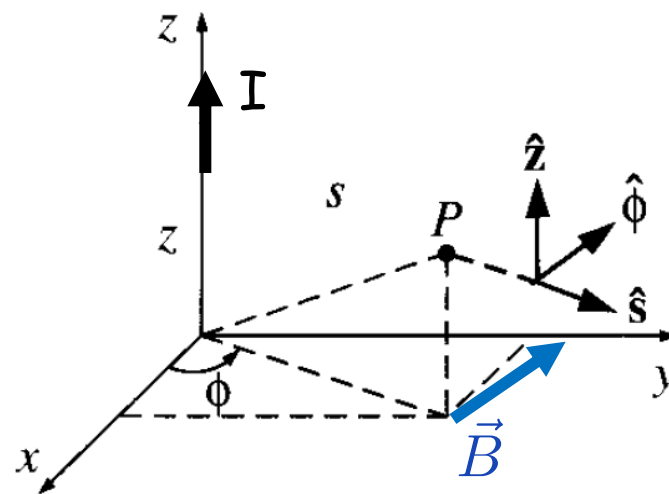
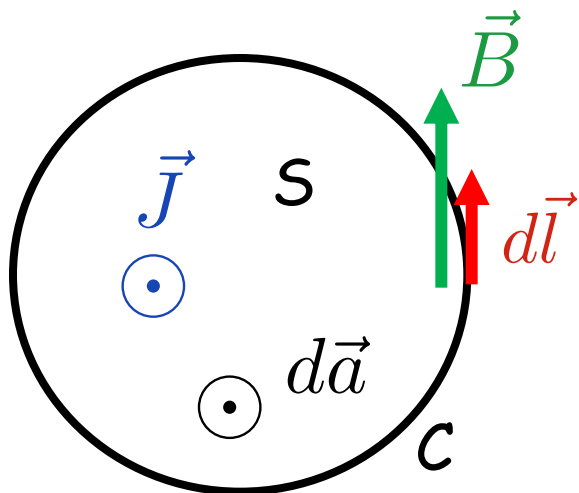
$$I = \int_S \vec{J} \cdot d\vec{a}$$

$$\int_S (\vec{\nabla} \times \vec{B}) \cdot d\vec{a} = \mu_0 \int_S \vec{J} \cdot d\vec{a}$$

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

Lei de Ampère
na forma diferencial

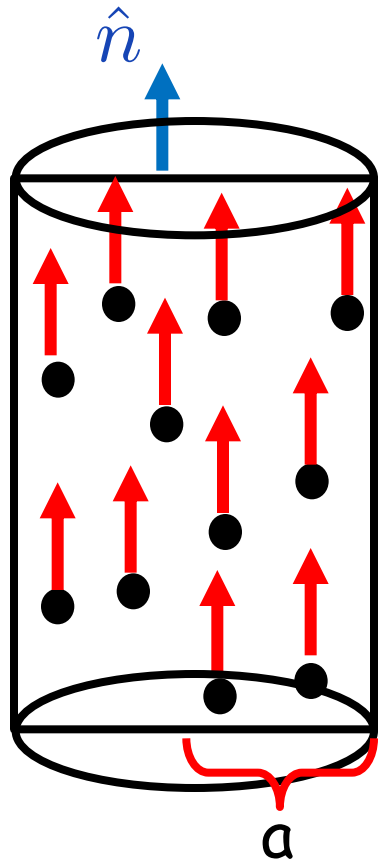
Atenção aqui: isto aparece muitas vezes !



$$\left\{ \begin{array}{l} \vec{B} = B \hat{\phi} \\ d\vec{l} = s d\phi \hat{\phi} \end{array} \right. \rightarrow \vec{B} \cdot d\vec{l} = B s d\phi$$

$$\oint_C \vec{B} \cdot d\vec{l} = \int_0^{2\pi} B s d\phi = 2\pi s B$$

Exemplo: fio cilíndrico de raio a com J constante



$$\vec{J} = J \hat{n} \quad J = \frac{I}{\pi a^2}$$

$$\oint_C \vec{B} \cdot d\vec{l} = \mu_0 I \quad I = \int_S \vec{J} \cdot d\vec{a} = \int_S J da$$

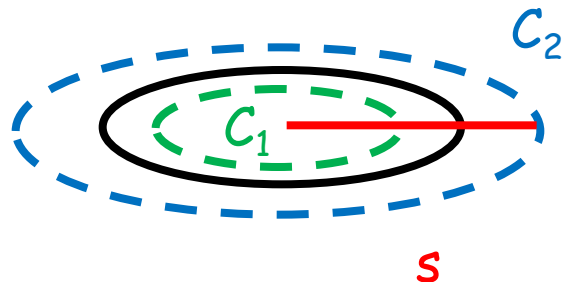
No interior do fio, em C_1 :

$$\oint_{C_1} \vec{B} \cdot d\vec{l} = \mu_0 \int_{S_1} J da = \mu_0 J \pi s^2$$

~~$$2\pi s B = \mu_0 J \pi s^2$$~~

$$B = \frac{\mu_0 J s}{2}$$

$$B = \frac{\mu_0 I s}{2\pi a^2} \hat{\phi}$$



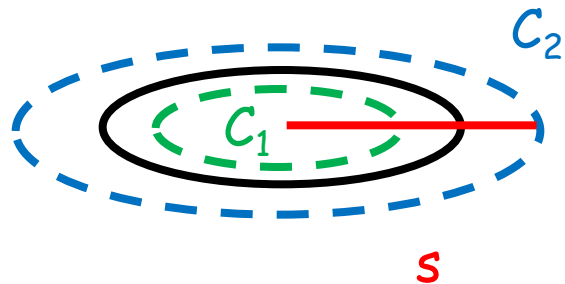
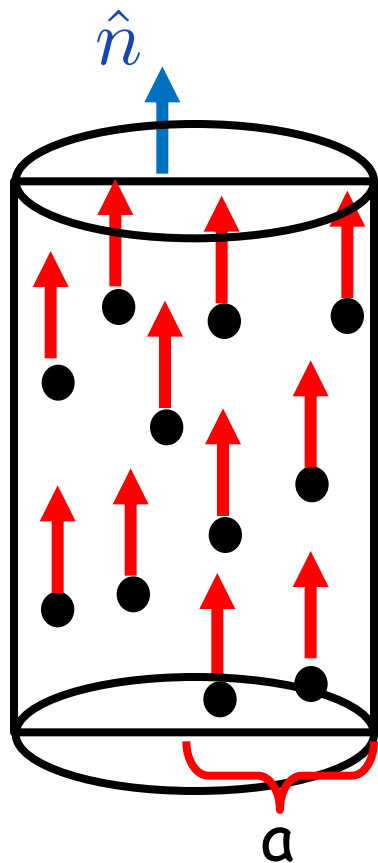
Exemplo: fio cilíndrico de raio a com J constante

No exterior do fio, em C_2 :

$$\oint_{C_2} \vec{B} \cdot d\vec{l} = \mu_0 \int_{S_2} J da = \mu_0 \frac{I}{\pi a^2} \pi a^2 = \mu_0 I$$

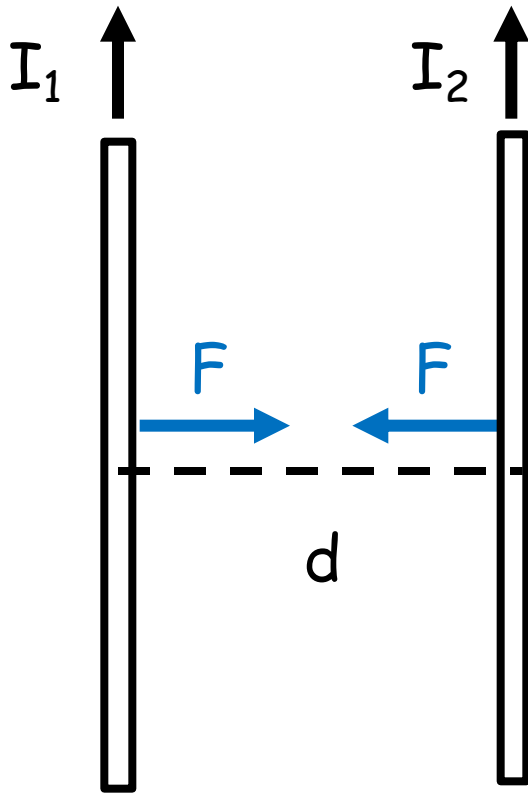
$$2 \pi s B = \mu_0 I$$

$$B = \frac{\mu_0 I}{2 \pi s} \hat{\phi}$$



Como sabemos que o campo magnético existe ?

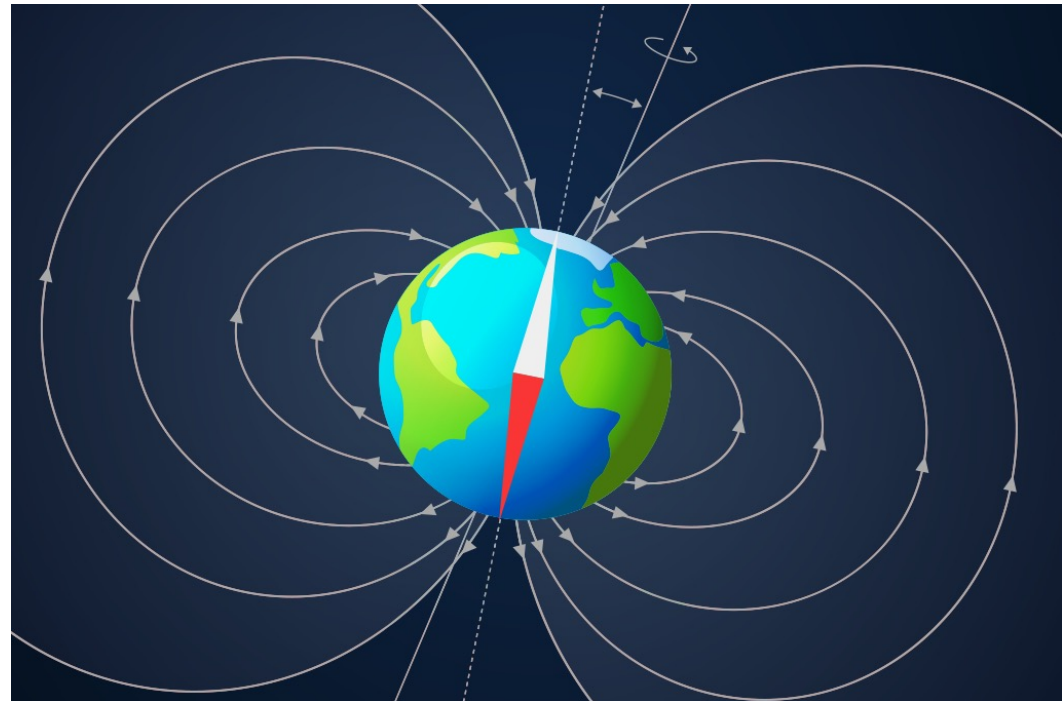
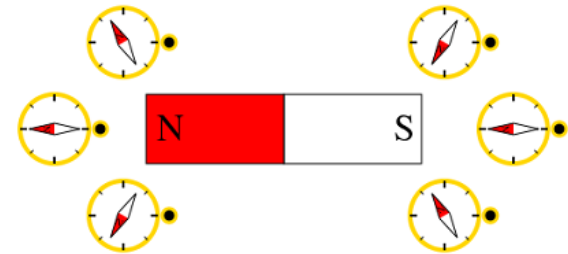
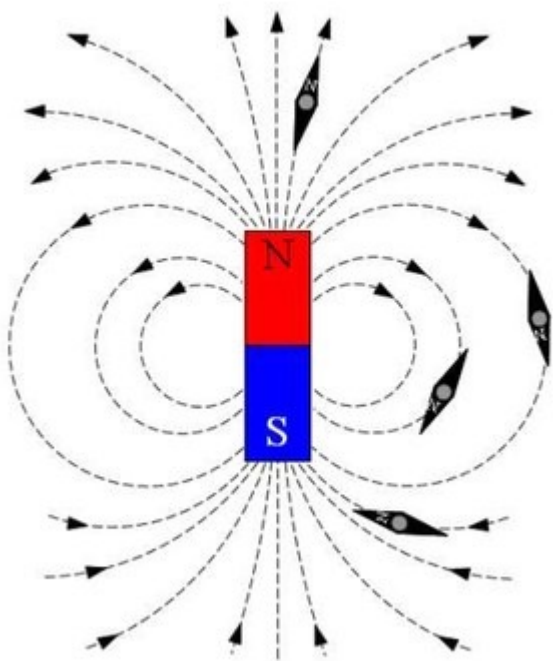
Dois fios percorridos por correntes se atraem !



$$\frac{F}{l} = \frac{\mu_0 I_2 I_1}{2 \pi d}$$

Como sabemos que o campo magnético existe ?

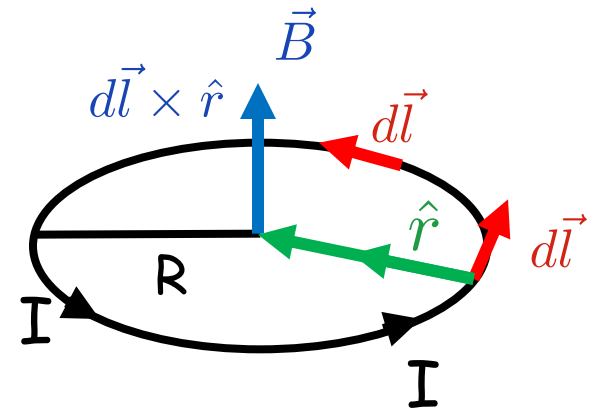
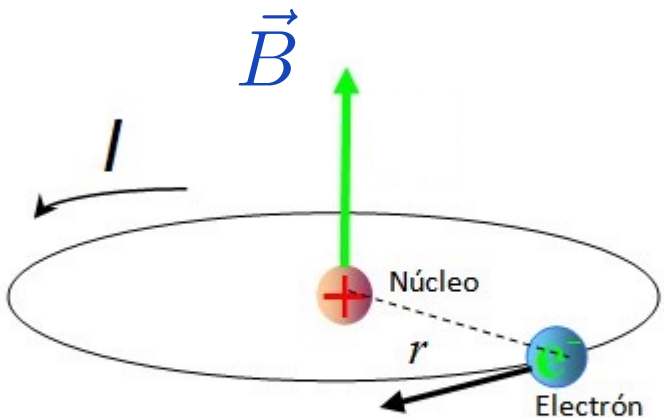
Com ímãs : { Ímãs produzem campos magnéticos ! A Terra é um ímã !
Ímãs "sentem" campos magnéticos ! A bússola é um ímã !



O que é um ímã ?

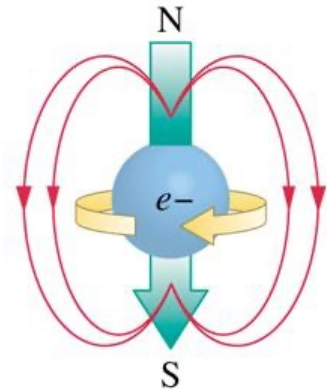
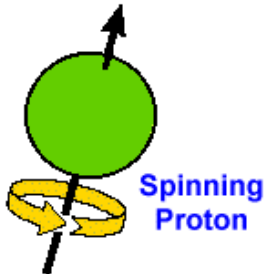
Origem do campo magnético do ímã:

eletrons em rotação orbital
spin



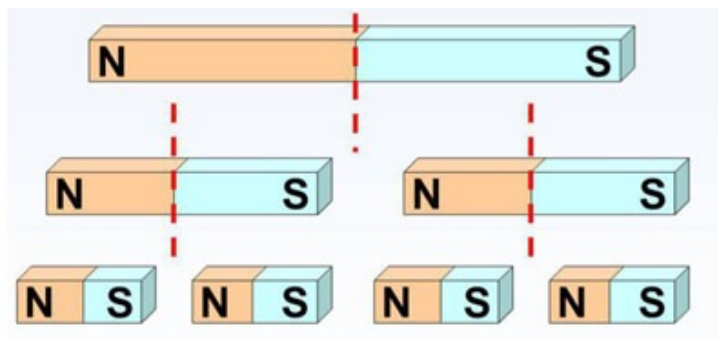
$$\vec{B} = \frac{\mu_0 I}{4\pi} \int \frac{d\vec{l} \times \hat{r}}{r^2} \quad \vec{B} = \frac{\mu_0 I}{2R} \hat{z}$$

Spin:

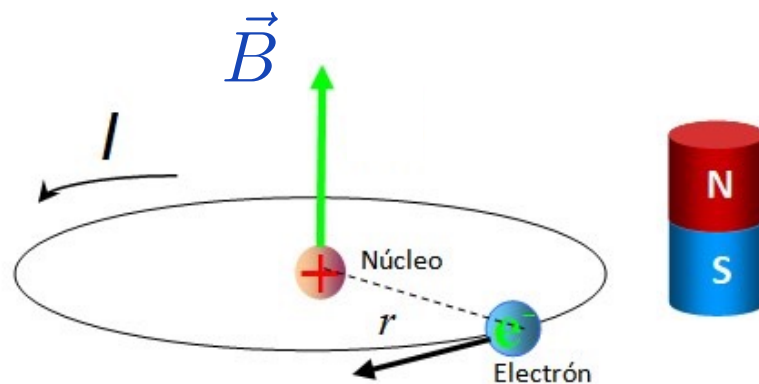


Inseparabilidade dos polos

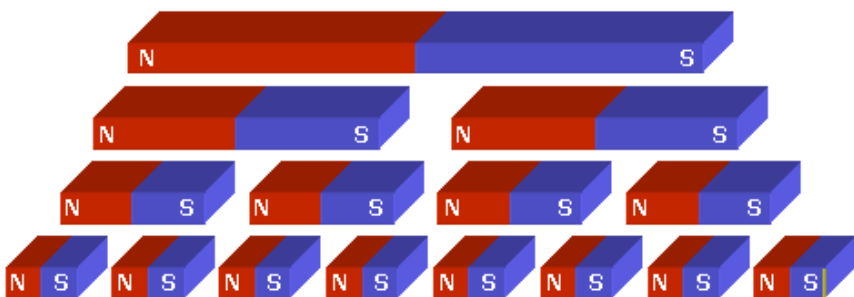
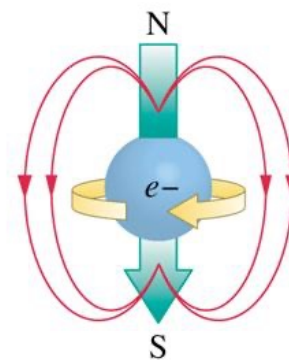
Parece que é impossível "quebrar" o ímã e separar norte e sul !



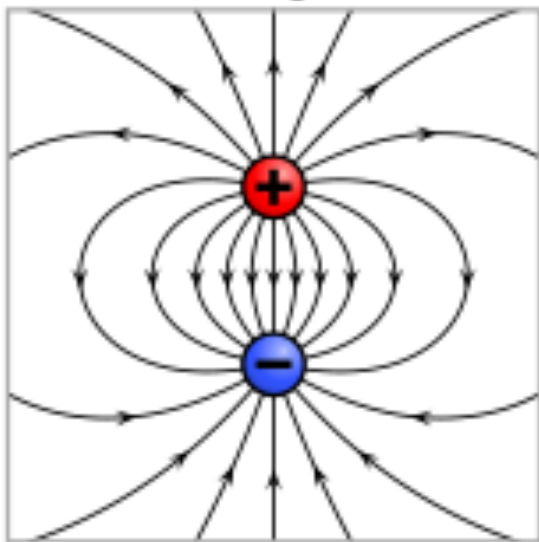
Um único átomo é um ímã !



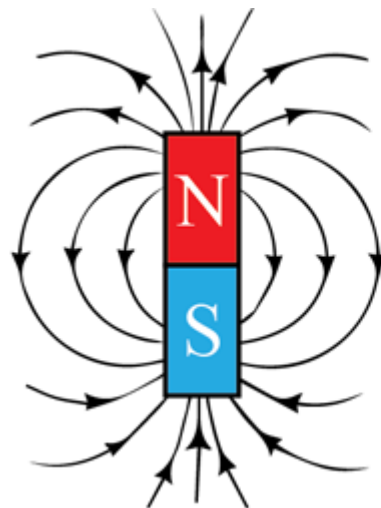
Um único elétron é um ímã !



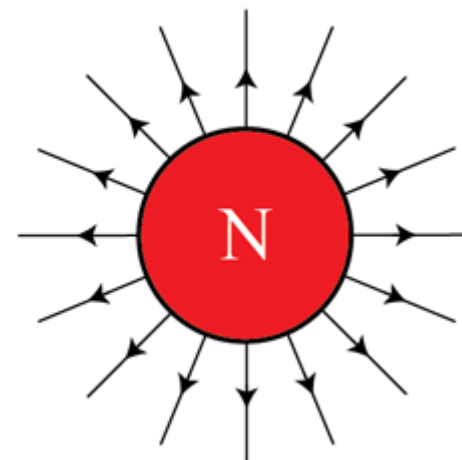
Parece que não existem monopolos magnéticos !



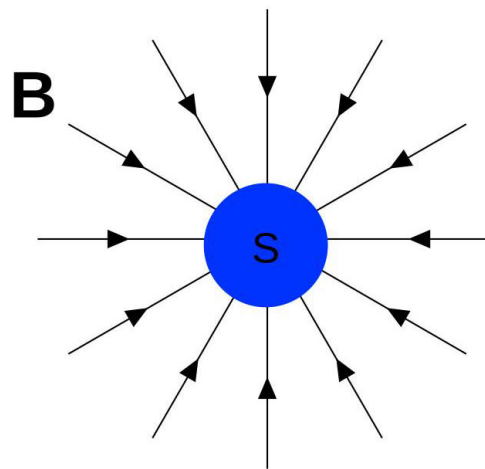
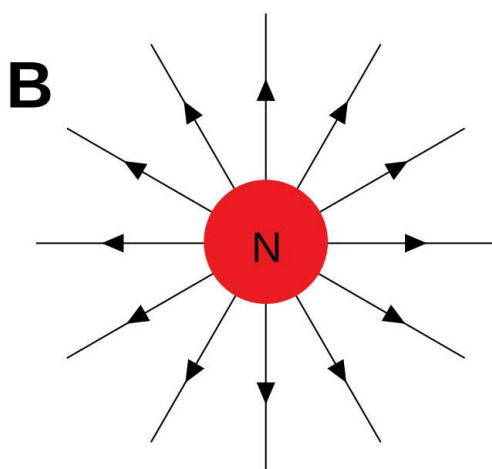
dipolo elétrico



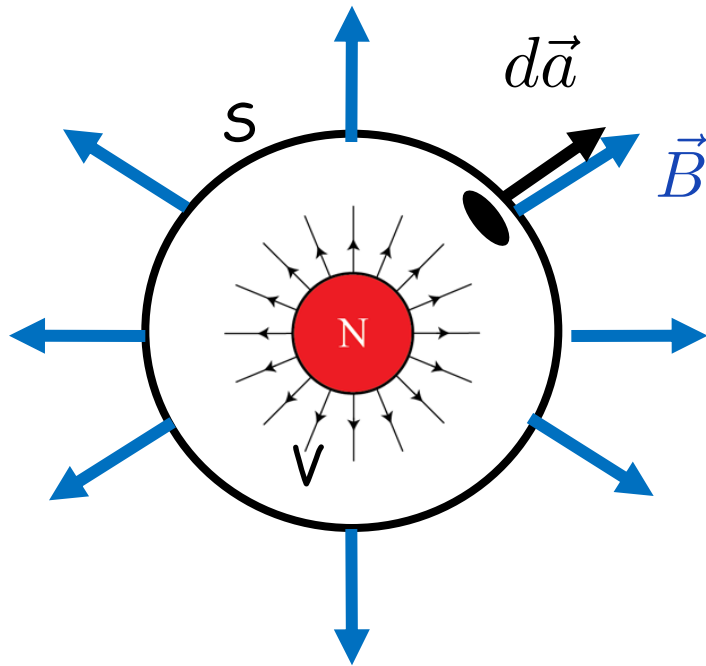
dipolo magnético



monopolo magnético



Lei de Gauss do magnetismo



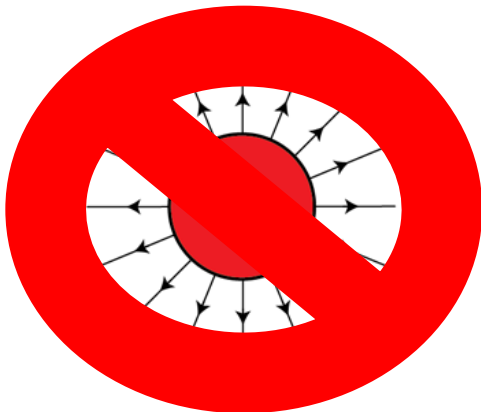
$$\oint_S \vec{E} \cdot d\vec{a} = \frac{Q_{int}}{\epsilon_0} \quad (\text{Gauss})$$

Vamos copiar para o campo B !

$$\oint_S \vec{B} \cdot d\vec{a} = \frac{Q_{mag}}{\epsilon_0} = 0$$

Teorema da divergência :

$$\oint_S \vec{B} \cdot d\vec{a} = \int_V \vec{\nabla} \cdot \vec{B} dV = 0$$



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

A gente tem mesmo certeza?

Não há uma lei que PROIBA a existência de monopólios magnéticos !

Sua existência foi proposta por Paul Dirac em 1931

A procura continua...

A new search for magnetic monopoles

Alex Lopatka

Citation: *Physics Today* 75, 4, 14 (2022); doi: 10.1063/PT.3.4975

View online: <https://doi.org/10.1063/PT.3.4975>

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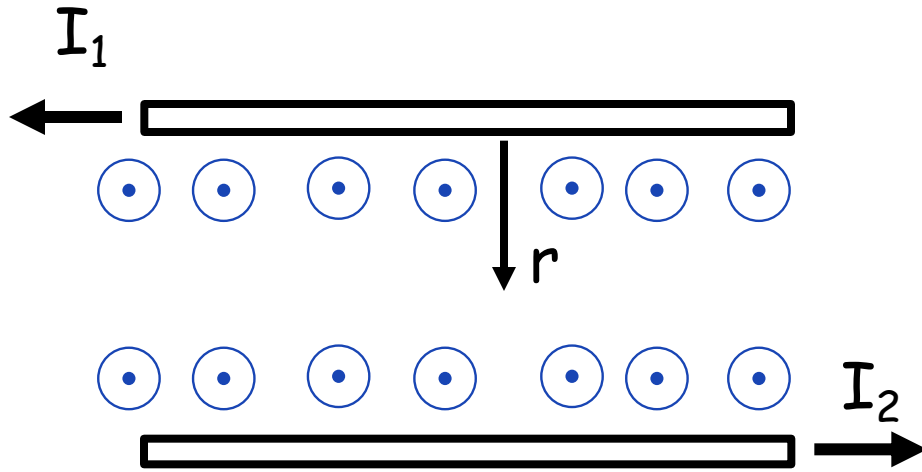


Paul Dirac
1902 - 1984

Colaboração MoEDAL : Monopole and Exotics Detector at the LHC

No LHC é produzido o campo magnético mais forte do Universo !

Campo produzido por dois fios paralelos com correntes opostas :

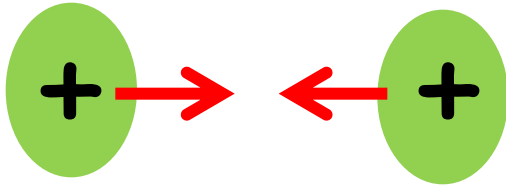


$$B = \frac{\mu_0 I}{2 \pi r}$$

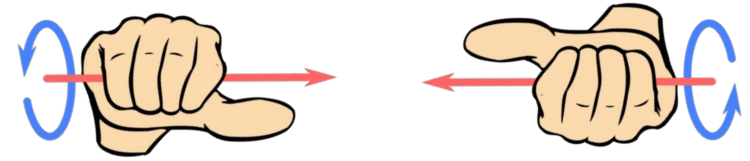
$$r \simeq 10^{-15} \text{ metros}$$

No LHC temos, ao invés de fios, dois feixes de ions positivos !

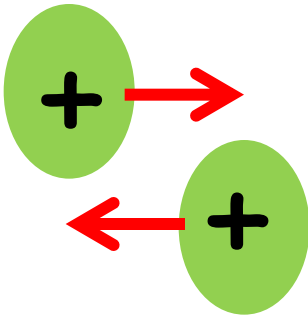
Campo magnético em colisões de íons pesados



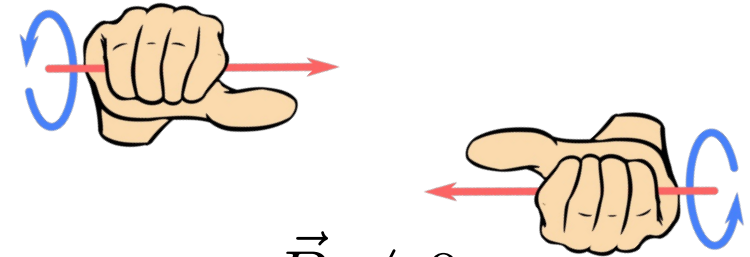
central



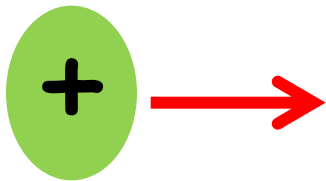
$$\vec{B} = 0$$



não-central



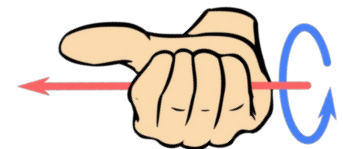
$$\vec{B} \neq 0$$

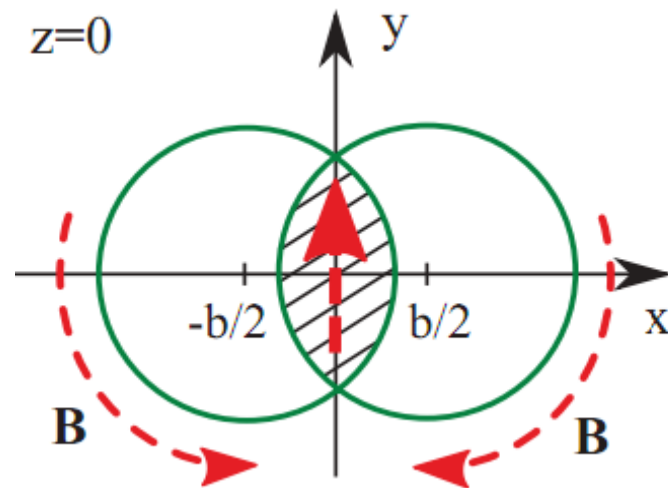
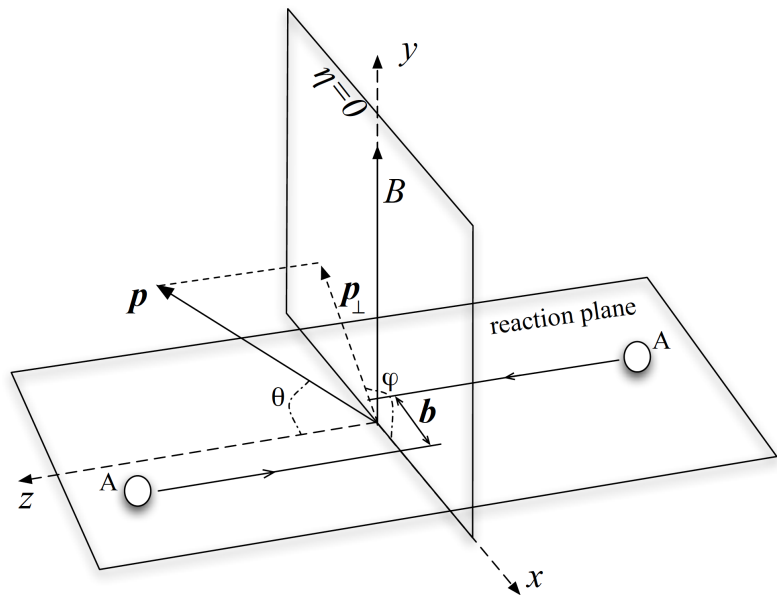


ultra
Periférica



$$\vec{B} \neq 0$$





$$B \propto \frac{\gamma Z e}{R^2}$$



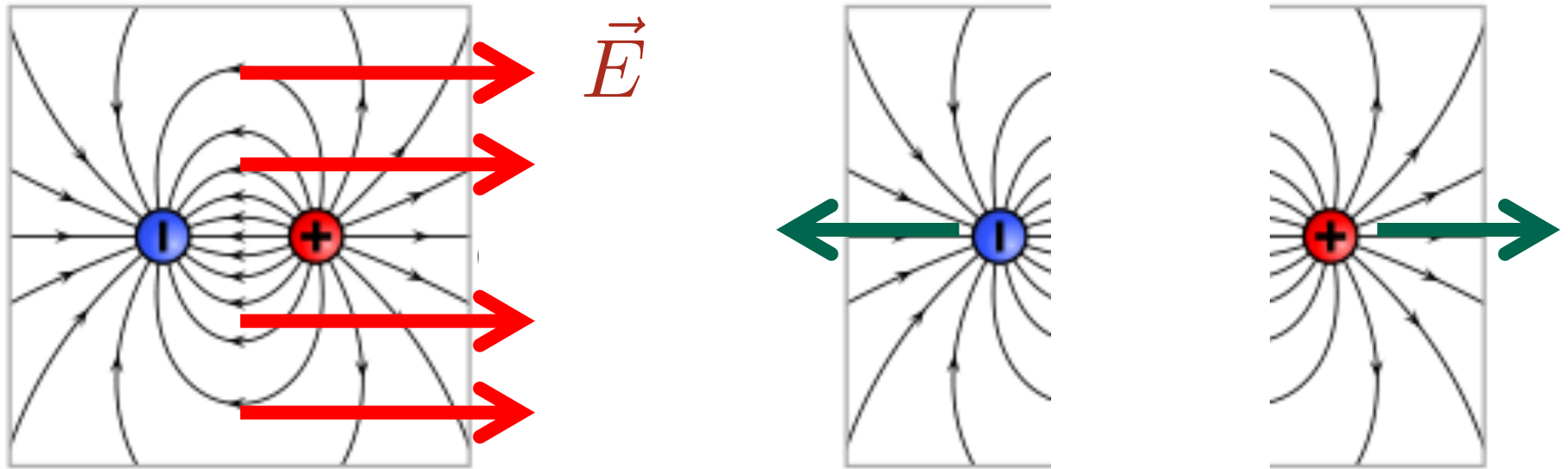
$$eB \approx m_{\pi}^2 \sim 10^{18} \text{ G}$$

Estrela de neutrons : $eB = 10^{14} \text{ G}$

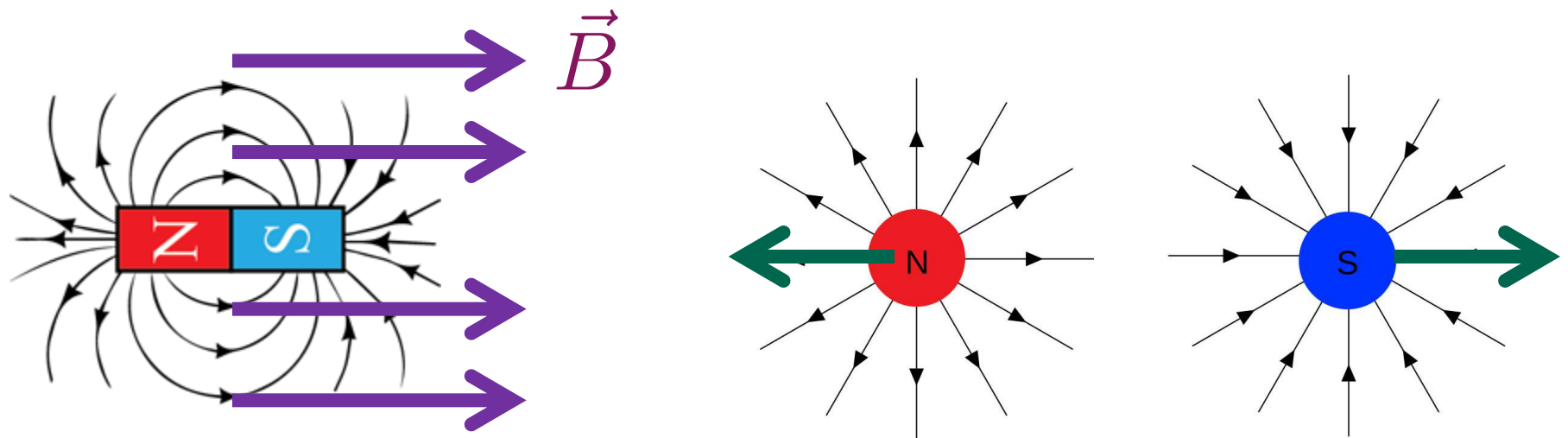
Magnetar: $eB = 10^{15} \text{ G}$

O mais intenso
da natureza!

Campo elétrico super-forte quebra o dipolo elétrico



Campo elétrico super-forte quebra o dipolo magnético

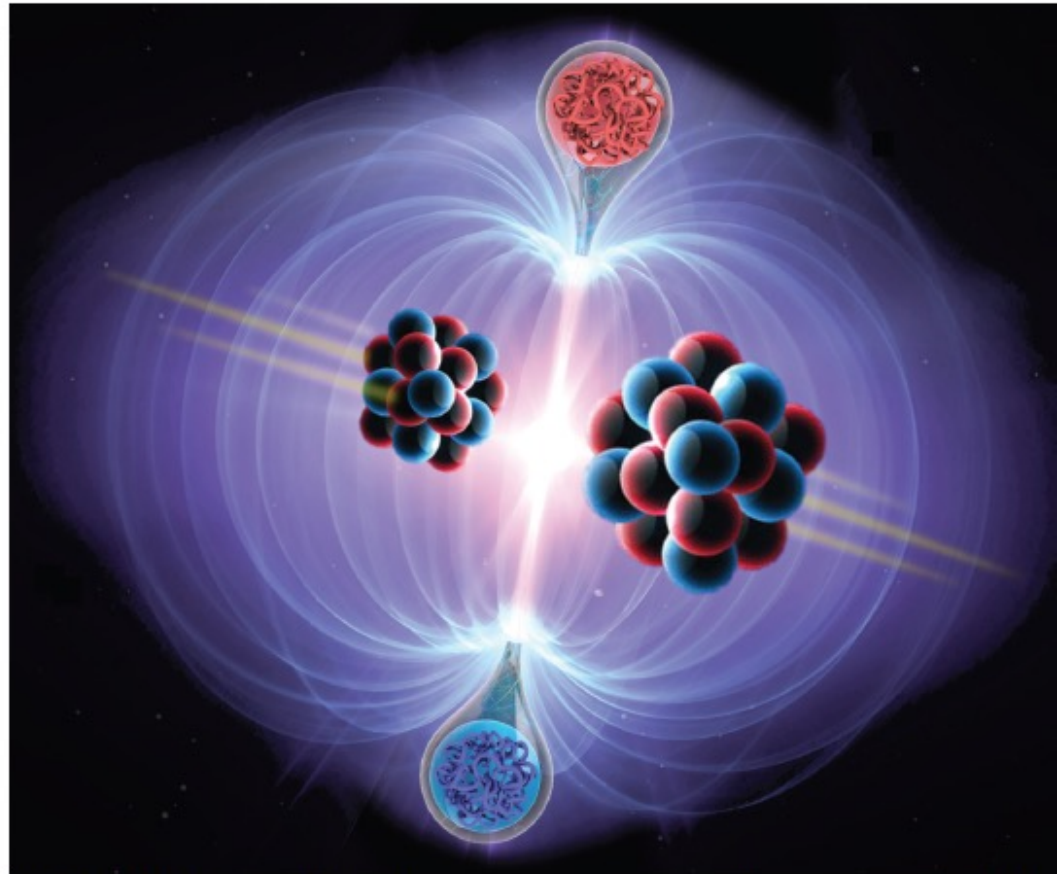


A new search for magnetic monopoles

The latest results from CERN's Large Hadron Collider have established a lower mass limit for the elusive hypothesized particle.

A magnet always has a north and a south pole. But nothing in classical electrodynamic theory or quantum mechanics says that magnetic monopoles can't exist. They're the hypothetical analogues to electric charges in Maxwell's equations. In fact, their existence would make the equations more symmetrical: Electric terms could be transformed to magnetic ones, and vice versa (see the article by Arttu Rajantie, *PHYSICS TODAY*, October 2016, page 40).

Magnetic monopoles could be point-like fundamental particles that carry magnetic charge, similar to electrons and described in 1931 by Paul Dirac.¹ Or they could be composite particles with a substructure, similar to neutrons or protons, as predicted by string theory, grand unified theories, and other explanations for physics beyond the standard model. Observing magnetic monopoles would pro-



THE COLLISION of two lead nuclei generates an exceptionally strong magnetic field. Magnetic monopoles and their antiparticles are theorized to be produced from the decay of that magnetic field, although they have yet to be observed. (Courtesy of James Pinfold, MoEDAL collaboration.)

Mas...até agora nada !

Equações de Maxwell

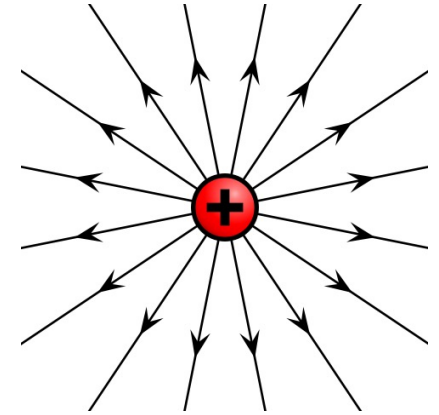
$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

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

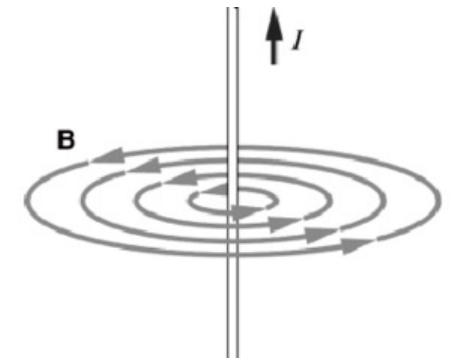
$$\vec{\nabla} \cdot \vec{B} = 0$$

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

E diverge mas
não "roda" !



B "roda" mas
não diverge !



Fim