

**Centro Federal de Educação Tecnológica de Santa Catarina**  
**Departamento Acadêmico de Eletrônica**  
**Retificadores**



# **Lei de Faraday e Lenz**

## **Auto-indutância e Indutores**

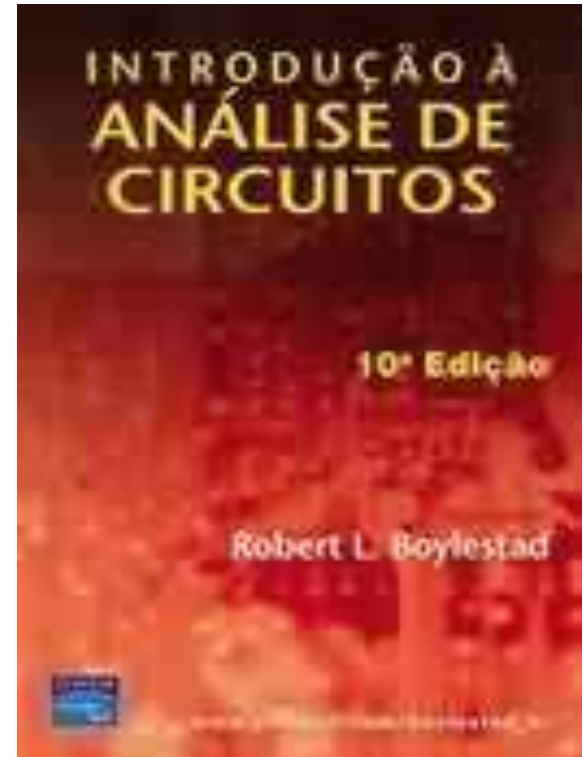
**Prof. Clóvis Antônio Petry.**

**Florianópolis, setembro de 2008.**

# Bibliografia para esta aula

## Capítulo 12: Indutores

1. Lei de Faraday;
2. Lei de Lenz;
3. Auto-indutância;
4. Tipos de indutores.

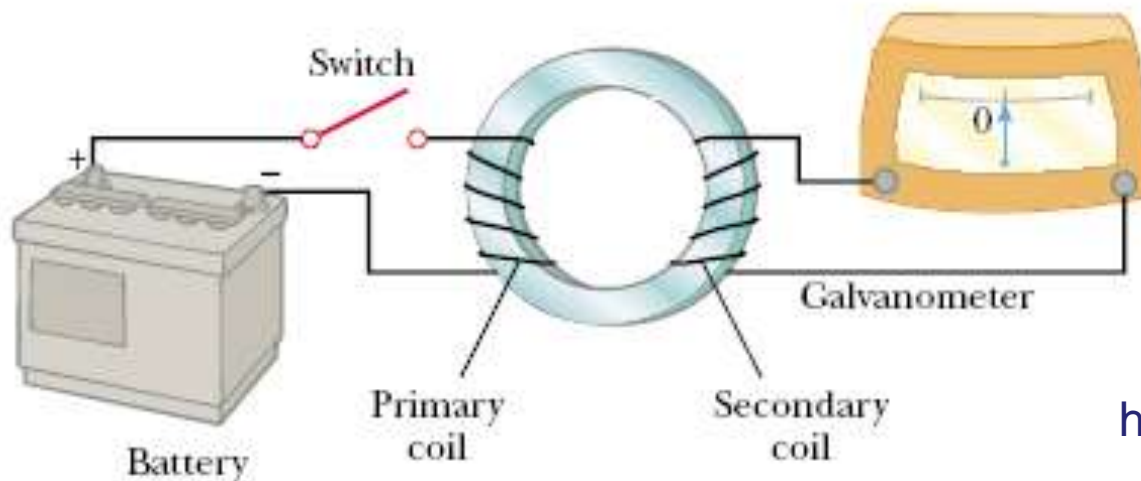


[www.cefetsc.edu.br/~petry](http://www.cefetsc.edu.br/~petry)

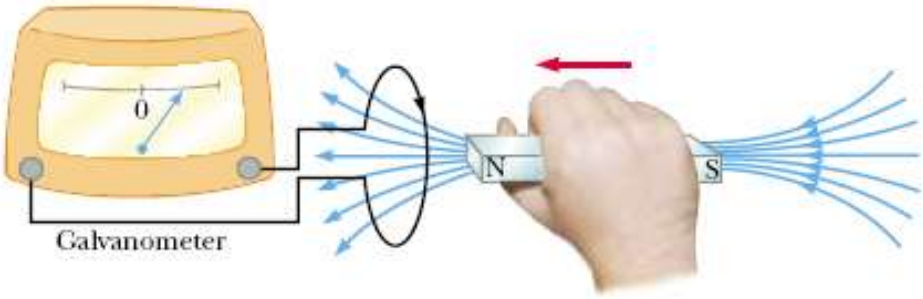
# Indução eletromagnética

## Experiência de Faraday:

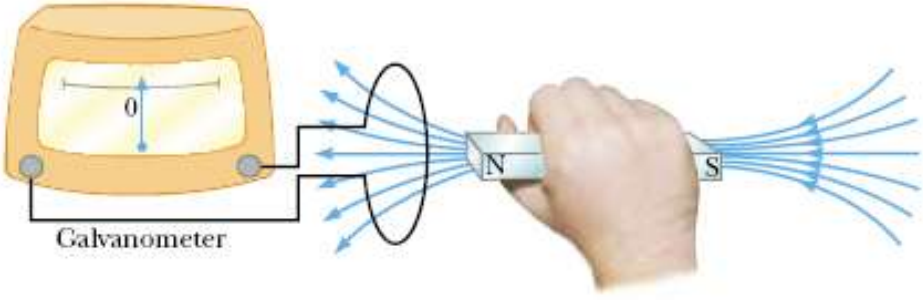
- No momento que a chave é fechada, o galvanômetro acusa uma pequena corrente de curta duração;
- Após a corrente cessar e durante tempo em que a chave permanecer fechada, o galvanômetro não mais acusa corrente;
- Ao abrir-se a chave, o galvanômetro volta a indicar uma corrente de curta duração, em sentido oposto ao observado no momento de fechamento da chave.



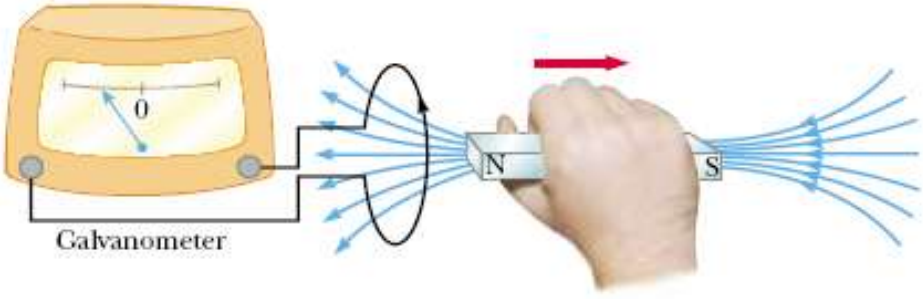
# Indução eletromagnética



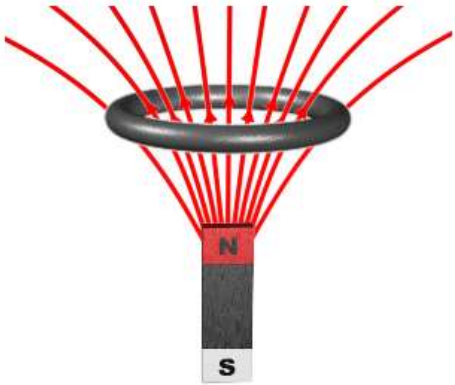
(a)



(b)



(c)

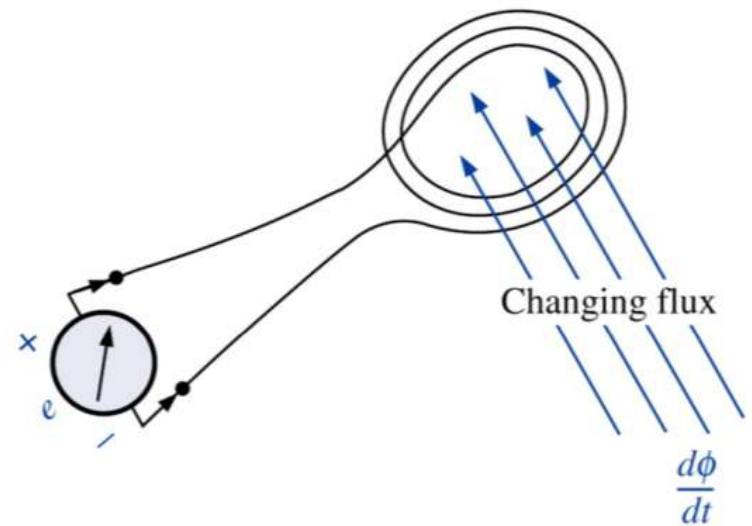
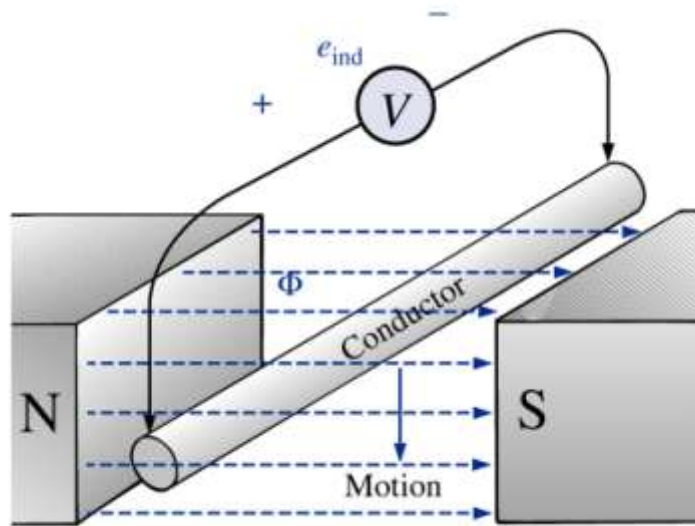


<http://micro.magnet.fsu.edu>

# Indução eletromagnética

A indução eletromagnética é regida por duas leis:

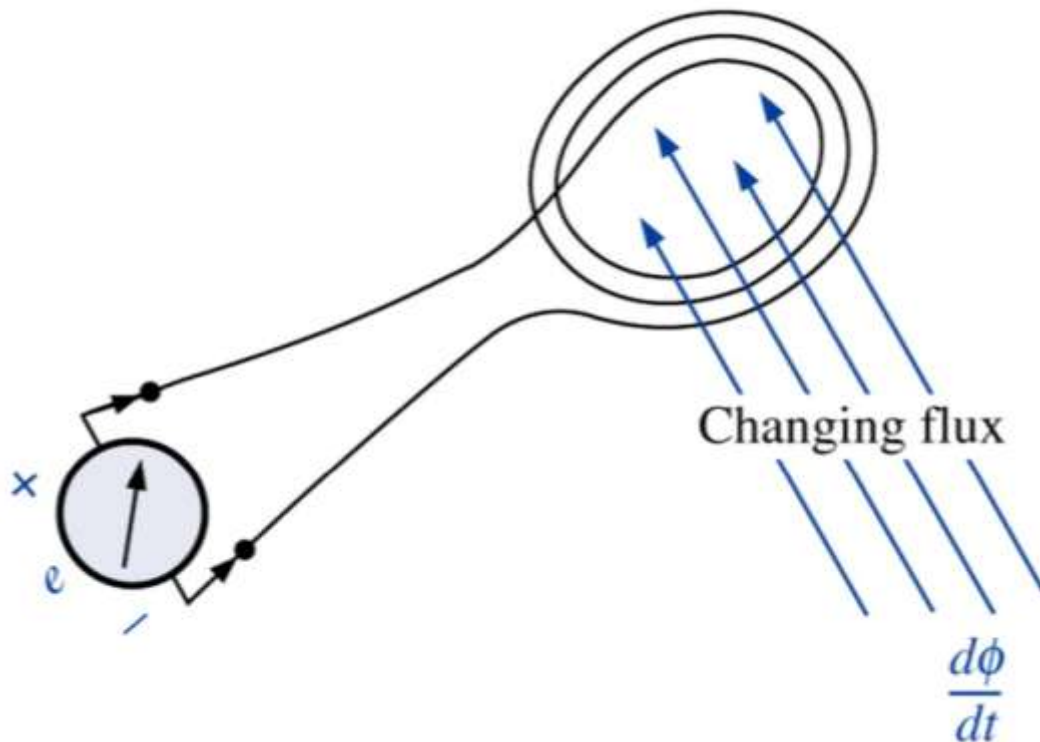
- Lei de Faraday;
- Lei de Lenz.



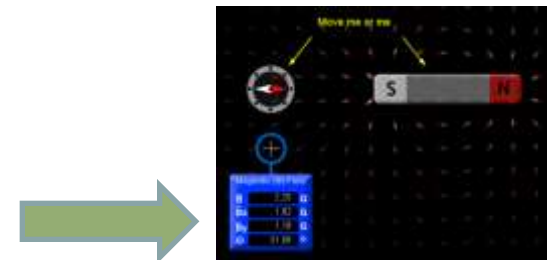
# Indução eletromagnética

## Lei da indução eletromagnética de Faraday:

Em todo condutor enquanto sujeito a uma variação de fluxo magnético é estabelecida uma força eletromotriz (tensão) induzida.



$$\varepsilon = N \frac{d\phi}{dt} \quad [\text{volts, V}]$$

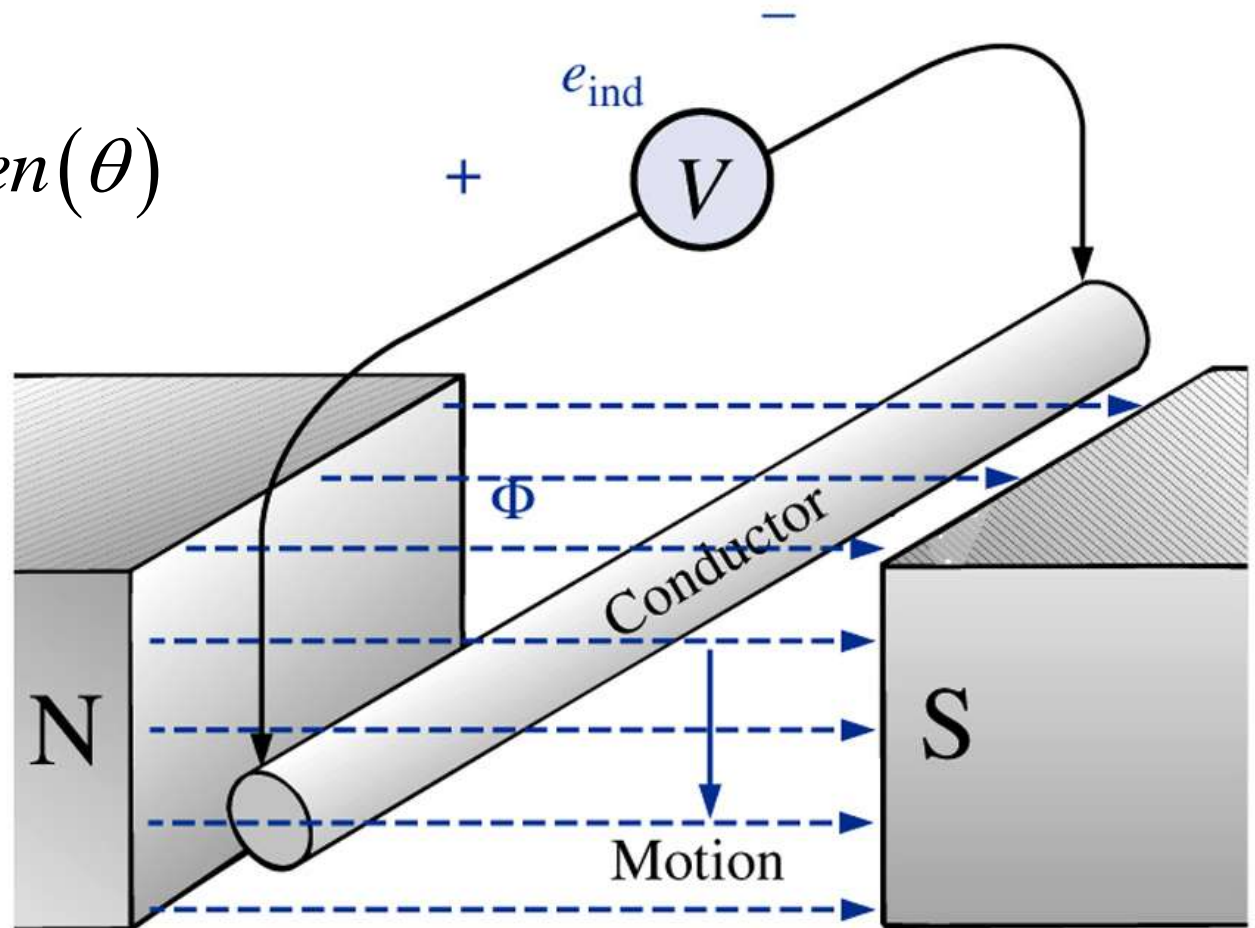


<http://phet.colorado.edu>

# Tensão induzida em condutores num campo

$$\varepsilon = -N \frac{d\phi}{dt}$$

$$\phi = B \cdot A \cdot \text{sen}(\theta)$$



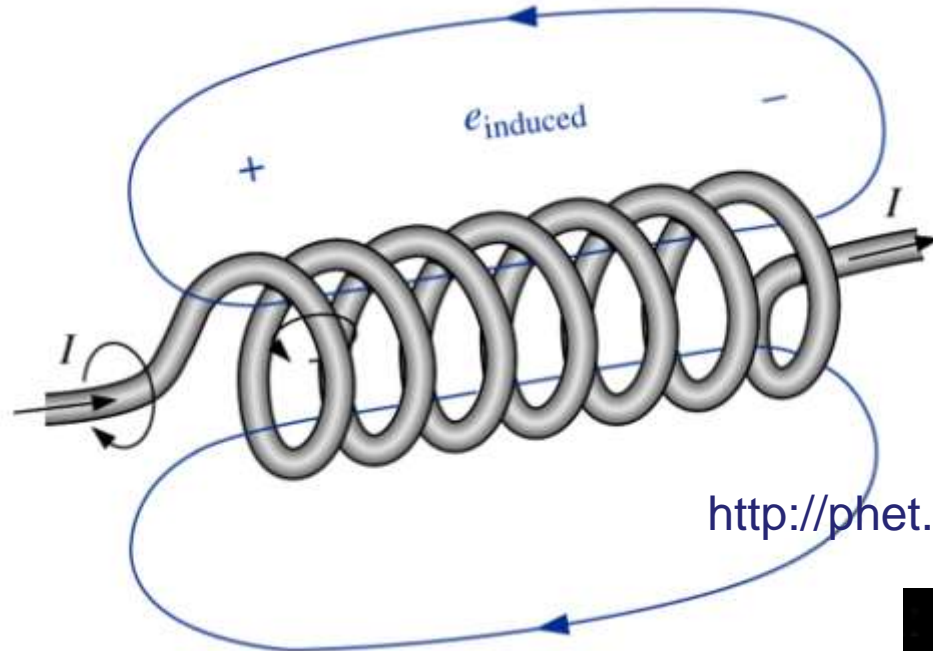
# Lei de Lenz

## Lei de Lenz:

O sentido da corrente induzida é tal que origina um fluxo magnético induzido, que se opõe à variação do fluxo magnético indutor.



$$\varepsilon = -N \frac{d\phi}{dt}$$



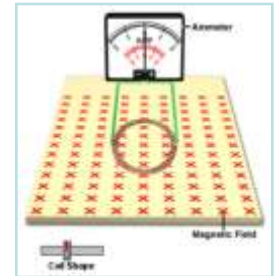
<http://phet.colorado.edu>

Um efeito induzido ocorre sempre de forma a se opor à causa que o produziu.

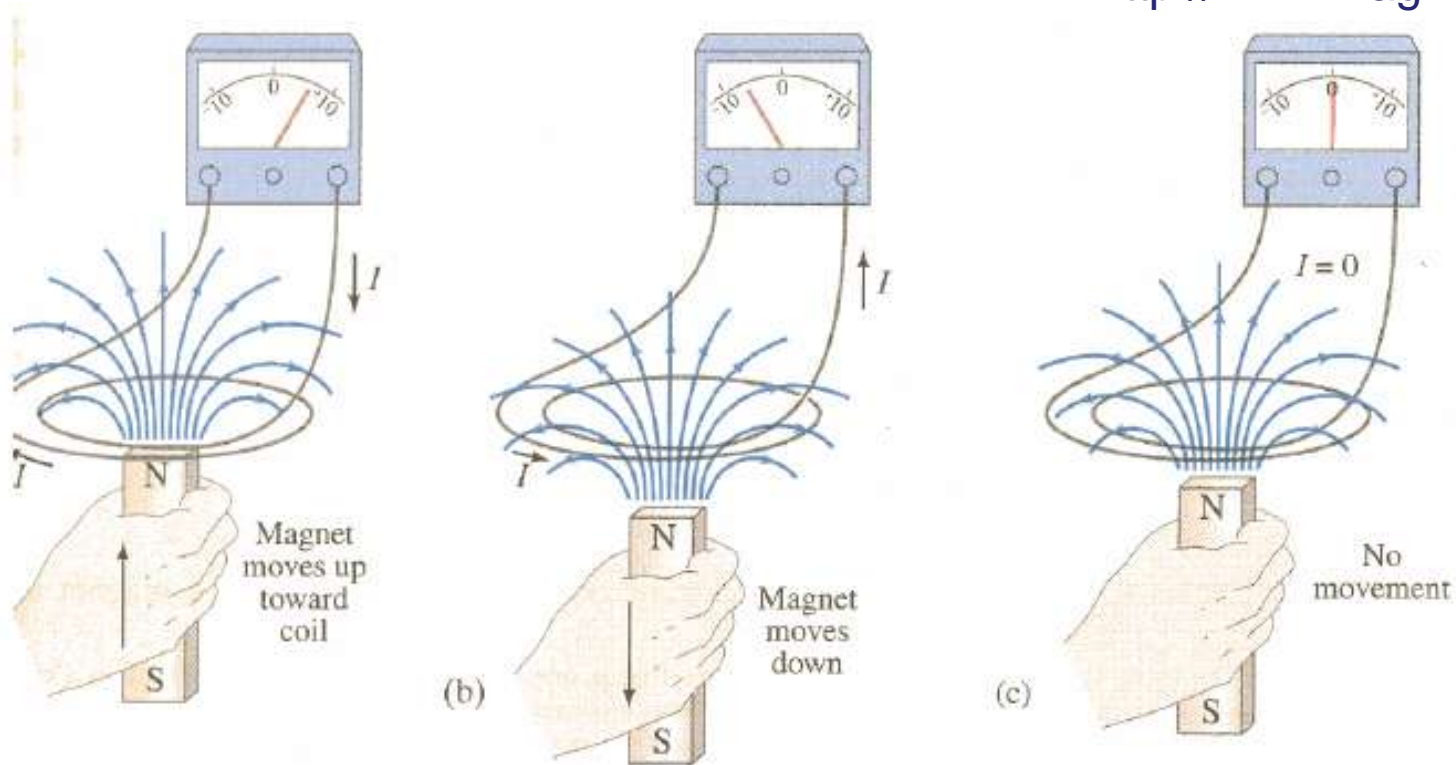


# Indução eletromagnética

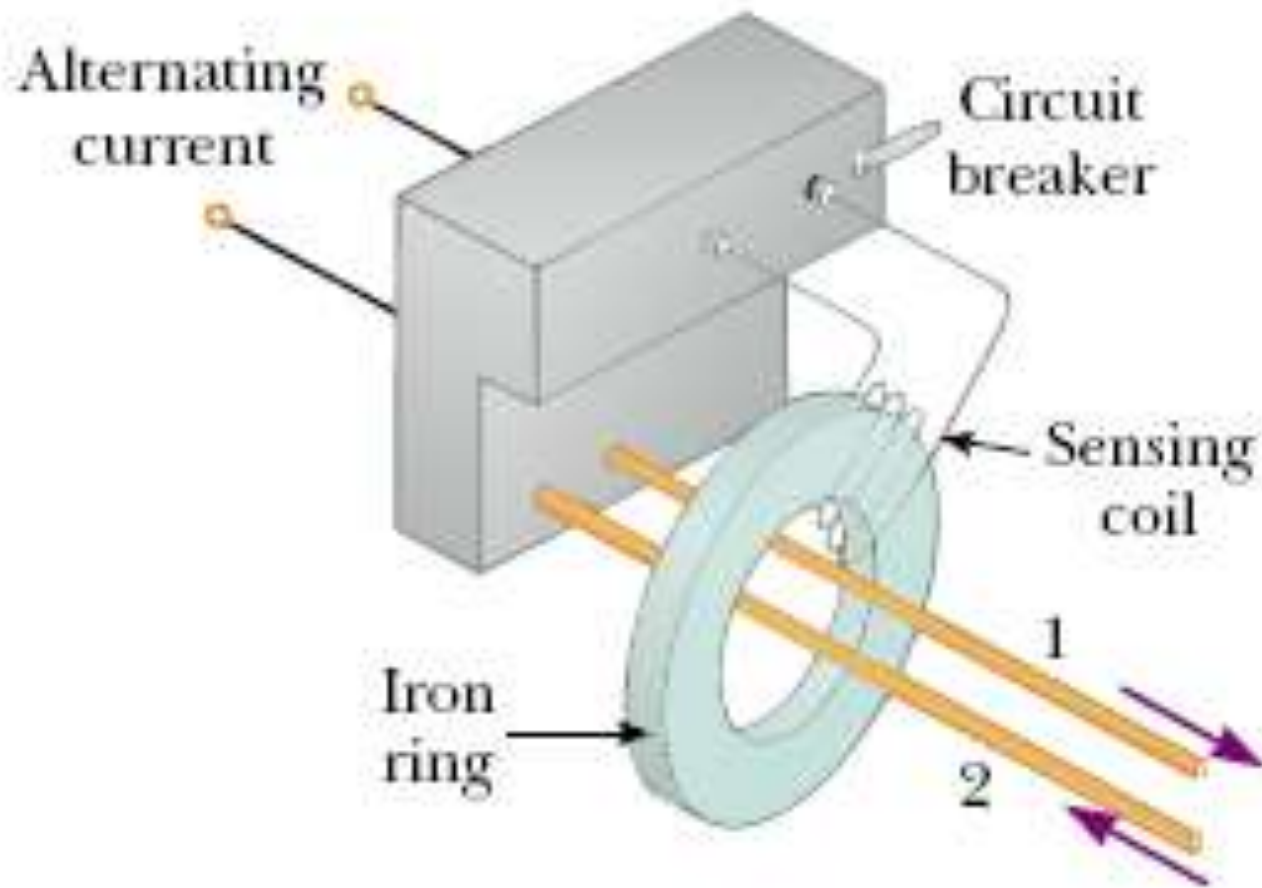
Com base nas leis da indução, explicar o comportamento do amperímetro na figura abaixo:



<http://www.magnet.fsu.edu>



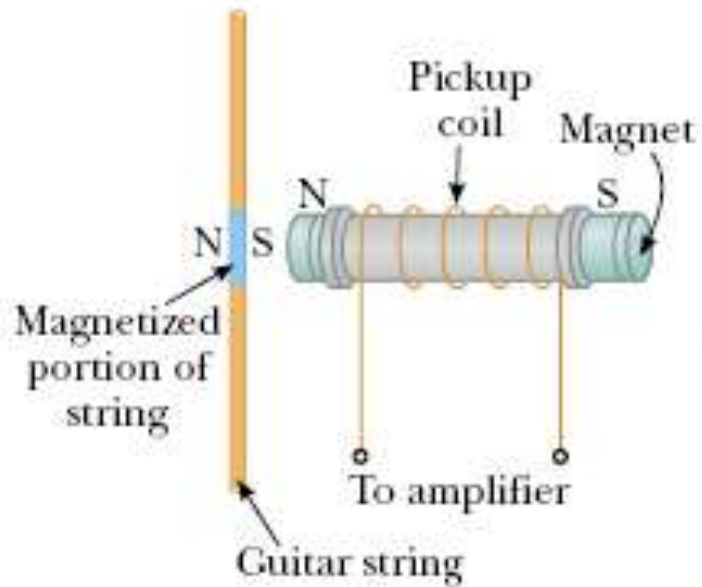
# Aplicações – Disjuntor diferencial



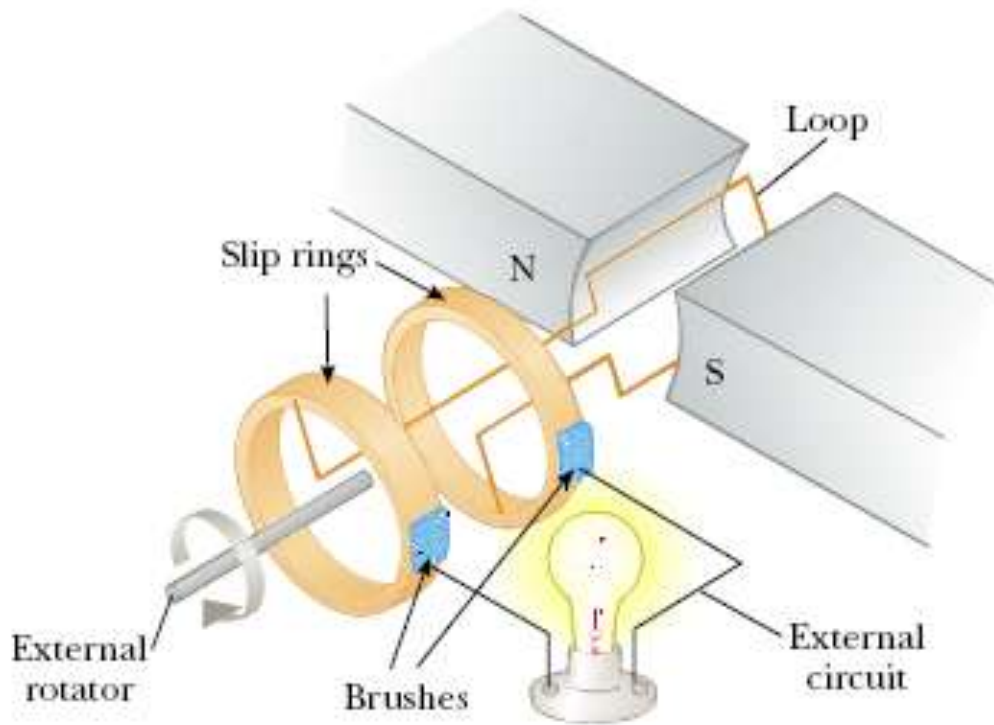
## Aplicações – Forno ou panela de indução



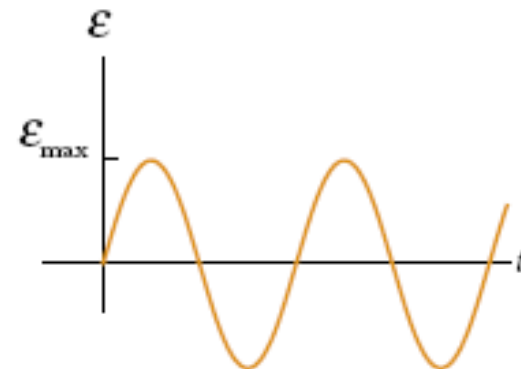
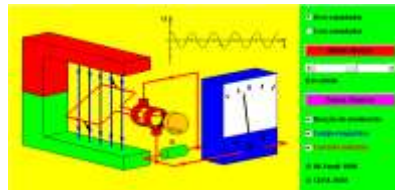
# Aplicações – Guitarra elétrica



# Aplicações – Geração de CA

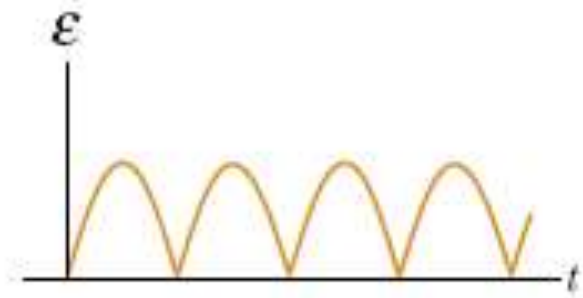
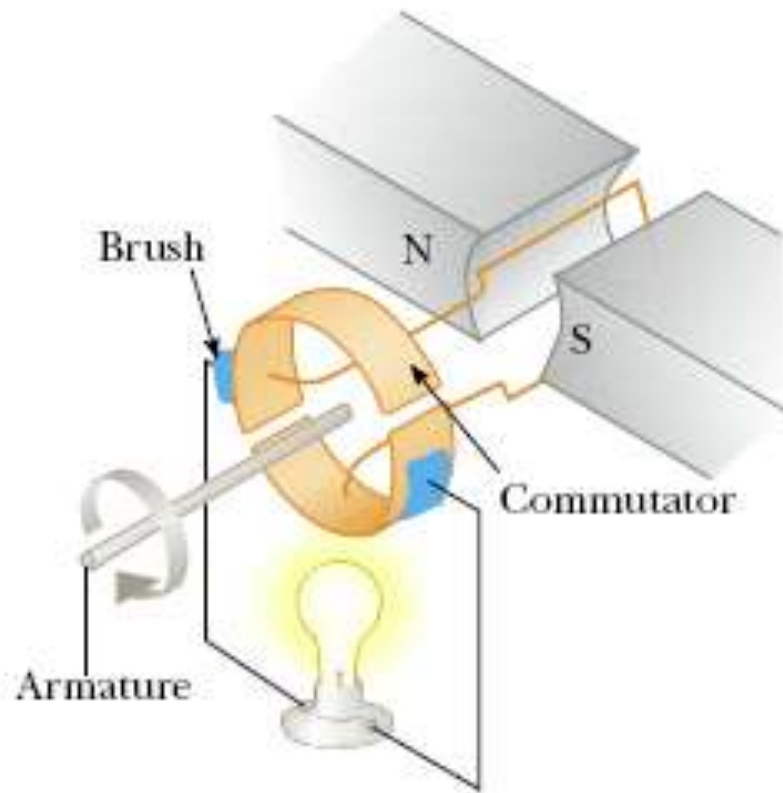


Applets em java →

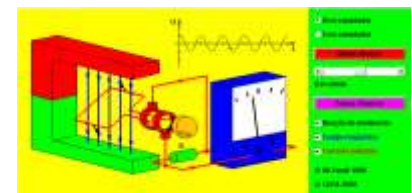


<http://www.walter-fendt.de/ph11br/>

# Aplicações – Gerador CC



Applets em java →

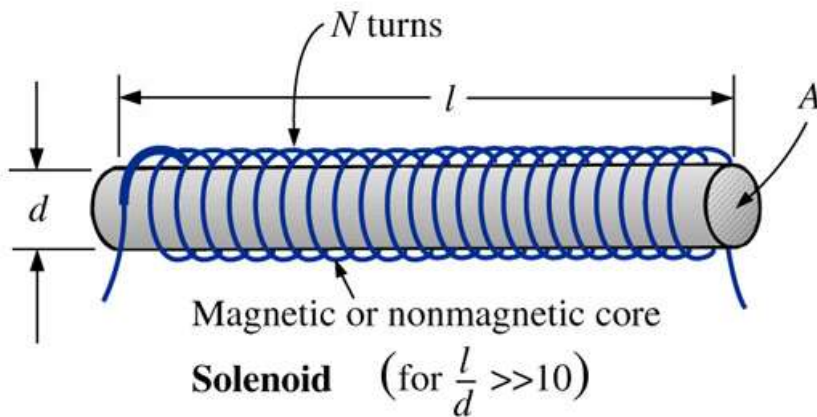


<http://www.walter-fendt.de/ph11br/>

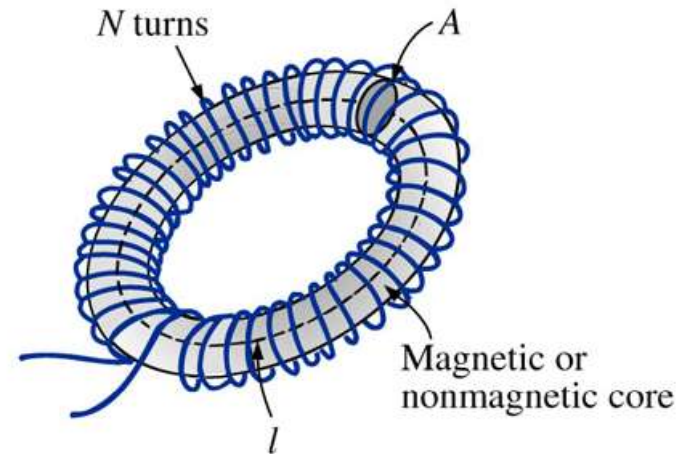
# Auto-Indutância

A propriedade de uma bobina de se opor a qualquer variação de corrente é medida pela sua auto-indutância ( $L$ ). A unidade de medida é o Henry (H).

$$L = \frac{N^2 \cdot \mu \cdot A}{l}$$



(a)

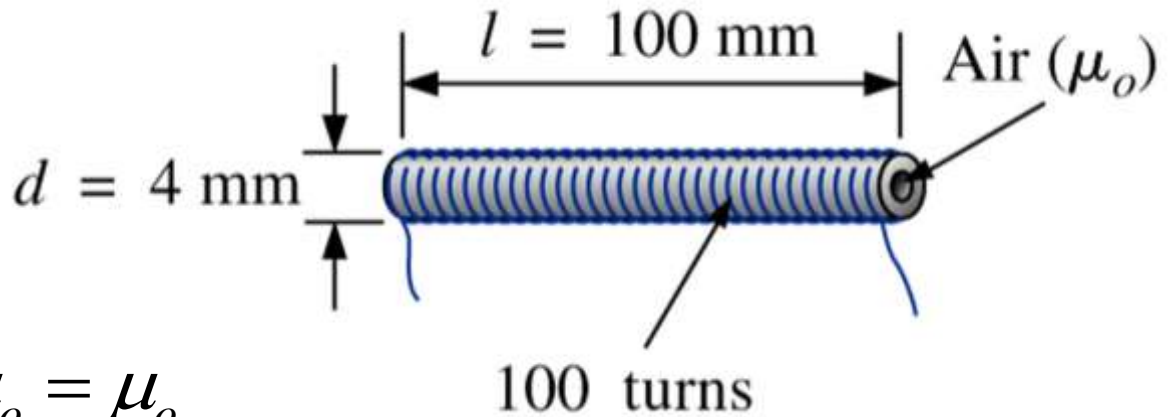


Toroid

(b)

# Auto-Indutância

Exemplo 12.1: Determine a indutância da bobina de núcleo de ar da figura abaixo:



$$\mu_r = 1$$

$$\mu = \mu_r \cdot \mu_o = 1 \cdot \mu_o = \mu_o$$

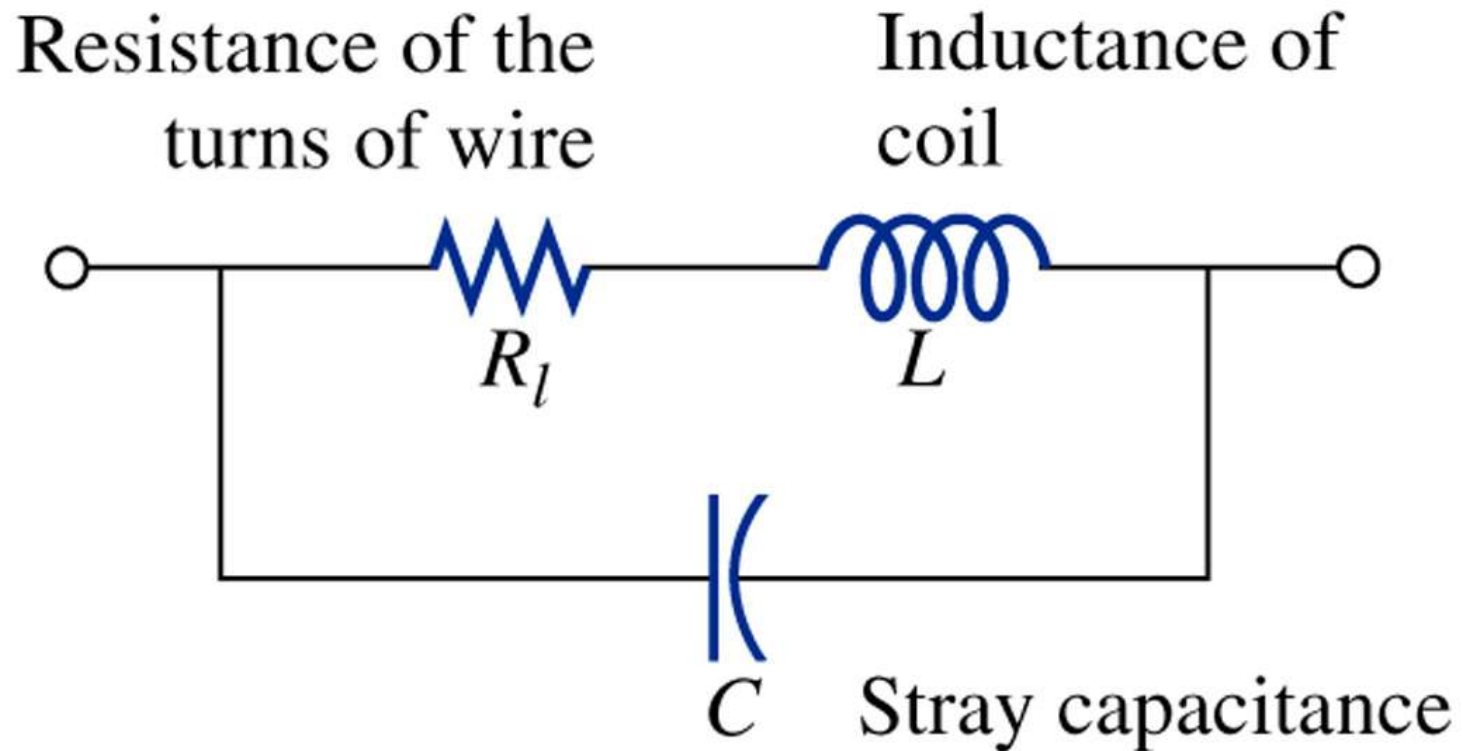
$$A = \frac{\pi \cdot d^2}{4} = \frac{\pi \cdot (4 \cdot 10^{-3})^2}{4}$$

$$L = \frac{N^2 \cdot \mu \cdot A}{l}$$

$$A = 12,57 \cdot 10^{-6} \text{ m}^2$$

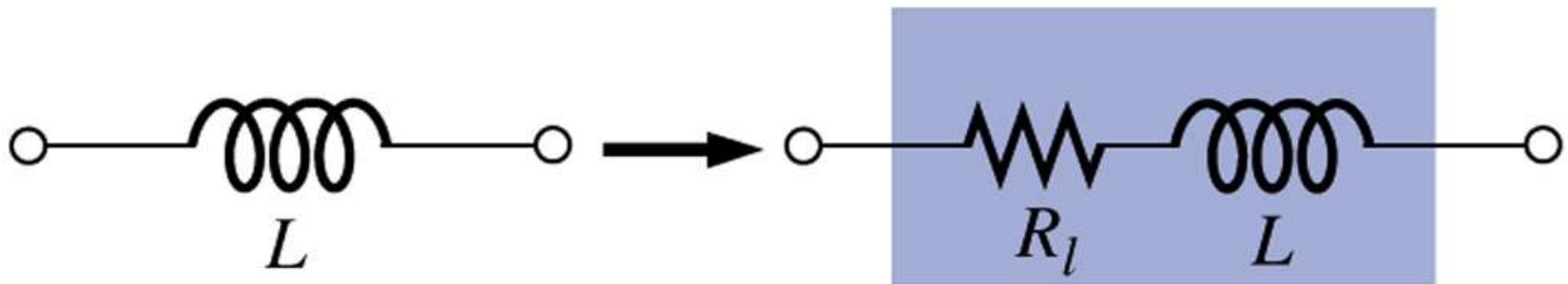
$$L = \frac{100^2 \cdot 4\pi \cdot 10^{-7} \cdot 12,57 \cdot 10^{-6}}{0,1} = 1,58 \mu\text{H}$$

# Circuito equivalente de um indutor



Circuito equivalente completo de um indutor

# Circuito equivalente de um indutor



Circuito equivalente prático de um indutor

# Símbolos de inductores



Air-core



Iron-core



Variable  
(permeability-tuned)

# Indutores na prática



# Projeto simplificado de indutores

**Bobinas longas:**

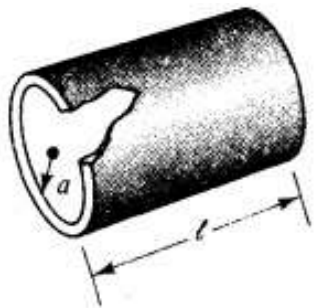
$$L = \frac{N^2 \cdot \mu \cdot A}{l} \quad \longrightarrow \quad N = \sqrt{\frac{L \cdot l}{\mu \cdot A}}$$

Onde:

- N – número de espiras da bobina;
- L – indutância [Henry, H];
- A – área do núcleo [m<sup>2</sup>];
- l – comprimento da bobina [m];
- $\mu$  – permeabilidade do núcleo [Wb/A·m].

# Projeto simplificado de indutores

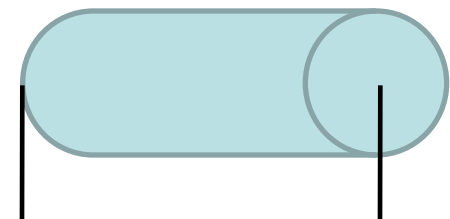
**Bobina de camada única com núcleo de ar:**



$$N = \sqrt{\frac{L \cdot (9 \cdot a + 10 \cdot l)}{39,5 \cdot a^2}}$$

Onde:

- N – número de espiras da bobina;
- L – indutância [micro Henry,  $\mu\text{H}$ ];
- a – raio do núcleo [m];
- l – comprimento da bobina [m].



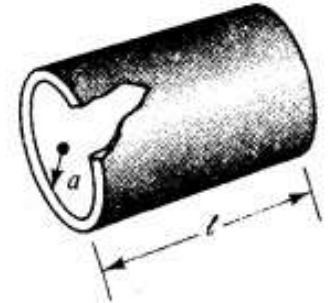
$$l = N \cdot D_{fio}$$

# Projeto simplificado de indutores

Bobina de camada única com núcleo de ar:

$$N = \sqrt{\frac{L \cdot (9 \cdot a + 10 \cdot l)}{39,5 \cdot a^2}}$$

$$l = N \cdot D_{fio}$$

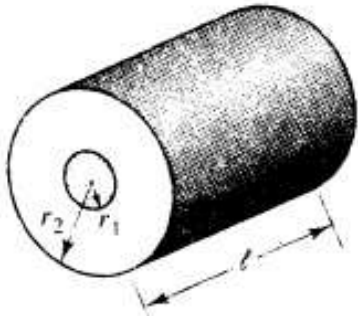


$$39,5 \cdot a^2 \cdot N^2 - 10 \cdot L \cdot D_{fio} \cdot N - 9 \cdot a \cdot L = 0$$

$$N = \frac{10 \cdot L \cdot D_{fio} \pm \sqrt{(-10 \cdot L \cdot D_{fio})^2 - 4 \cdot (39,5 \cdot a^2) \cdot (-9 \cdot a \cdot L)}}{2 \cdot (39,5 \cdot a^2)}$$

# Projeto simplificado de indutores

**Bobina de diversas camadas com núcleo de ar:**



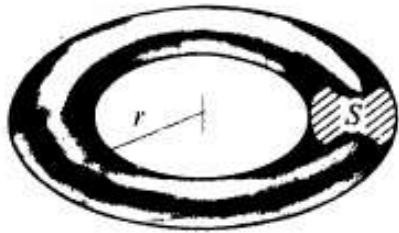
$$N = \sqrt{\frac{L \cdot (6 \cdot r_1 + 9 \cdot l + 10 \cdot (r_2 - r_1))}{31,6 \cdot r_1^2}}$$

Onde:

- N – número de espiras da bobina;
- L – indutância [micro Henry,  $\mu\text{H}$ ];
- $l$  – comprimento da bobina [m];
- $r_1$  – raio interno [m];
- $r_2$  – raio externo [m].

# Projeto simplificado de indutores

## Núcleos toroidais:



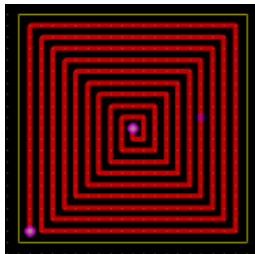
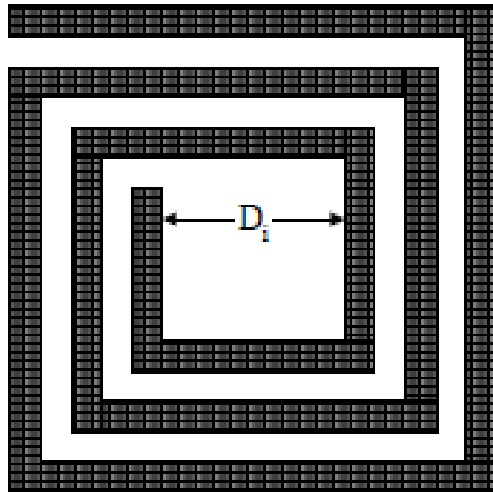
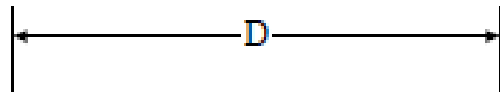
$$N = \sqrt{\frac{2\pi \cdot r \cdot L}{\mu \cdot A}}$$

Onde:

- N – número de espiras da bobina;
- L – indutância [Henry, H];
- A – área do núcleo [m<sup>2</sup>];
- $\mu$  – permeabilidade do núcleo [Wb/A·m];
- r – raio do toroide [m].

# Projeto simplificado de indutores

Indutor planar:



$$\text{Se } D_i = 0$$

$$L \approx 8,5 \cdot 10^{-10} \cdot D \cdot N^{\frac{5}{3}}$$

De acordo com:

Inductor Calculations Techniques - Part II: Approximations and Handbook Methods

From: [www.marctt2.com/induct2.pdf](http://www.marctt2.com/induct2.pdf)

Inductor Calculations Techniques - Part II: Approximations and Handbook Methods

Part II: Approximations and Handbook Methods

Mar T. Thompson, Ph.D.

INDEX OF SYMBOLS

- a Area (see label for unit)
- A Coil cross section
- B Coil axial thickness
- b Coil radial thickness
- B Length of square coil
- D Wire-to-wire spacing
- d Inductance and impedance
- L Coil length
- N Number of turns or coil
- N, P Core depth and constant
- Q Quality factor (Q)
- r, r' Turn length of printed pattern
- T Turn width
- W, L Inductance length of rectangular coil
- W, L Inductance perimeter of the square or circular coil

1. INTRODUCTION

In the first part of this two-part series on inductor calculations techniques, approximate equations and handbook methods are given for circular inductors that do not include axial thickness to obtain from inductance. A set of relations is also given which is useful for finding the inductance of many different loop shapes. Included are inductance calculations for polygons, disk coils, spiral-length inductors, and the printed spiral. To cover other areas the given methods require modifications. In the continuation we will investigate and the full equations may be found in the reference given. Many of the other relations work on inductor patterns. In English units, the new design handbooks have been converted to SI units with conversion factors in the new and length units in centimeters.

2. RELEVANT TERMS

Inductance calculation software can generally give results in SI units, and work in the SI system. In SI units, the unit of inductance is the henry (H), which is defined as the ratio of the induced voltage to the rate of change of current. In SI units, the unit of length is the meter (m), and the unit of area is the square meter (m<sup>2</sup>).

The value is an approximate value of the inductance of a circular inductor. See also the reference given in the text.

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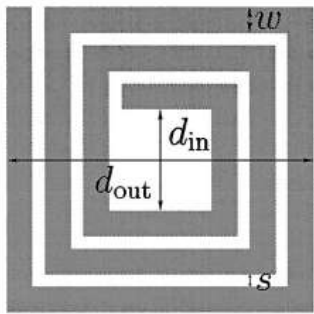
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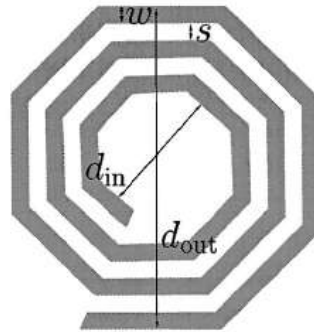
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# Projeto simplificado de indutores

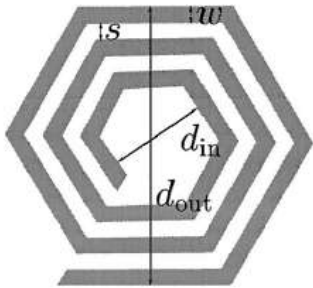
## Indutor planar:



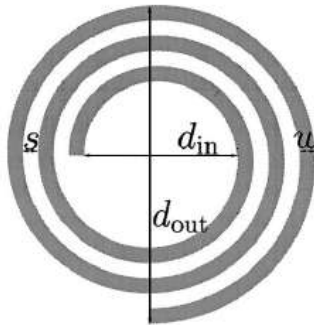
(a)



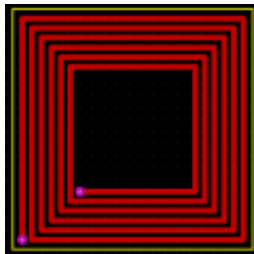
(b)



(c)



(d)



$$L = k_1 \cdot u_o \cdot \frac{n^2 \cdot d_{avg}}{1 + k_2 \cdot \rho}$$

$$k_1 = 2,34$$

$$k_2 = 2,75$$

$$d_{avg} = \frac{d_{out} + d_{in}}{2}$$

$$\rho = \frac{d_{out} - d_{in}}{d_{out} + d_{in}}$$

De acordo com:



# Projeto de indutores



## Indutor 01 – convencional com núcleo de ar:

- Indutância:  $L = 100$  a  $200 \mu\text{H}$ , definida como:

$$L = 100 \mu + \text{Ordem no diário} \cdot 2$$

Exemplo:

$$L = 100 \mu + \text{Ordem no diário} \cdot 2$$

$$L = 100 \mu + 1 \cdot 2 = 102 \mu\text{H}$$

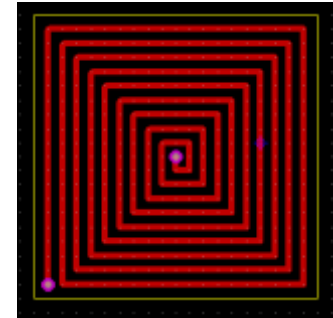
$$L = 100 \mu + 36 \cdot 2 = 172 \mu\text{H}$$

- Núcleo de ar;
- Diâmetro: livre, conforme o carretel ou molde;
- Comprimento: livre;
- Número de camadas: livre;
- Corrente:  $I = 1 \text{ A}$ ;
- Área do condutor: conforme tabela no site, para corrente especificada;
- Individual;
- Relatório (parte 1) deve conter no mínimo:
  - Capa, sumário, introdução, desenvolvimento (projeto), ensaios, foto, conclusão, referências bibliográficas, etc.
- Prazo de entrega: 30/10 (logo após o feriado do dia do servidor).

# Projeto de indutores

## Indutor 02 – planar em circuito impresso:

- Indutância:  $L = 1,5 \text{ nH}$ ;
- Núcleo de ar;
- Dimensões, conforme projeto;
- Corrente:  $I = 1 \text{ A}$ ;
- Individual;
- Na PCI deve ser impresso o nome do aluno e data;
- Relatório (parte 2) deve conter no mínimo:
  - Capa, sumário, introdução, desenvolvimento (projeto), ensaios, foto, conclusão, referências bibliográficas, etc.
- Prazo de entrega: 30/10 (logo após o feriado do dia do servidor).



# Na próxima aula

## Capítulo 11: Circuitos magnéticos

1. Tensão induzida;
2. Resposta transitória.

