3. PROXIMITY SENSOR

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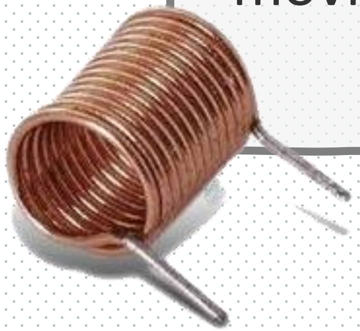
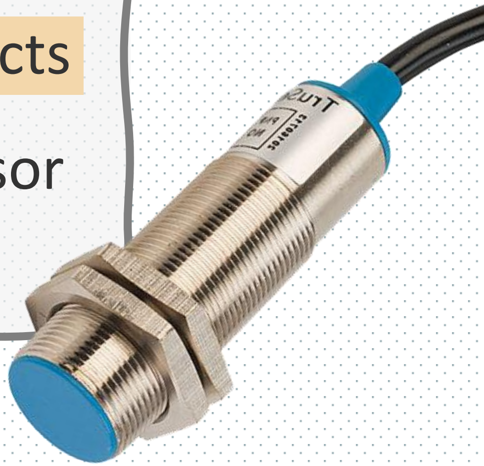
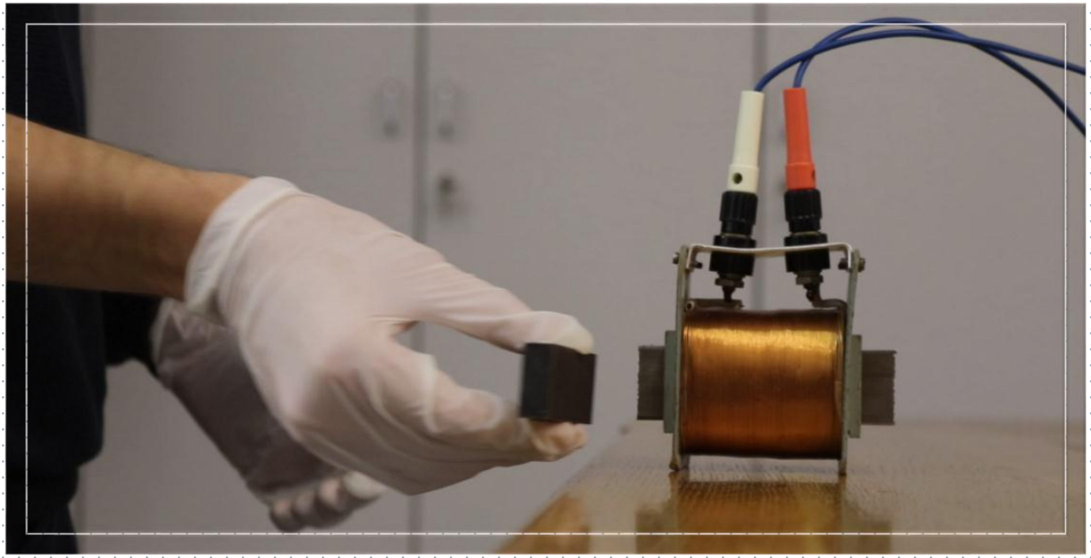
Proximity Sensor

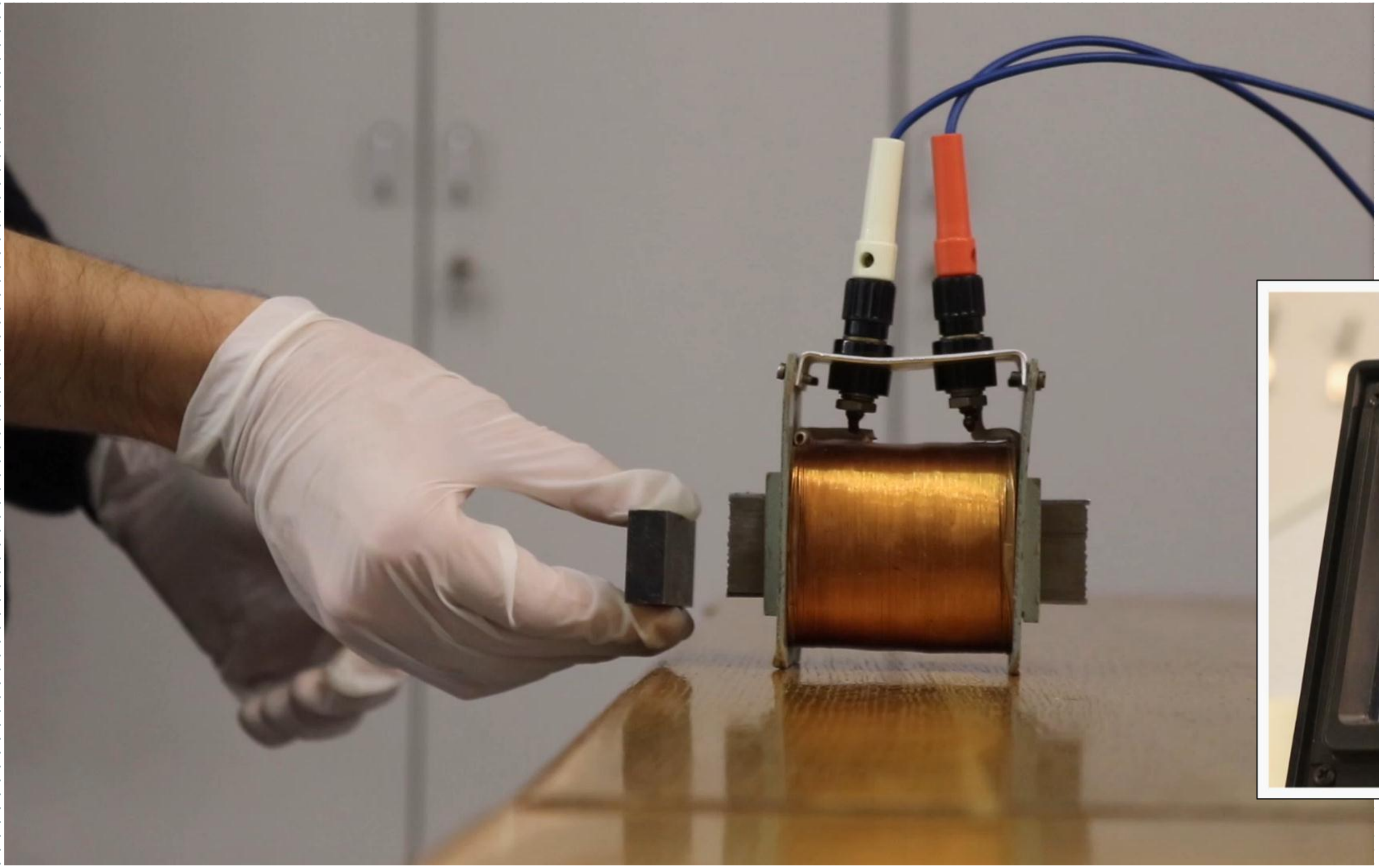
A simple passive inductive sensor can detect ferromagnetic objects moving through its magnetic field. Construct such a passive sensor and investigate its characteristics such as sensing range.

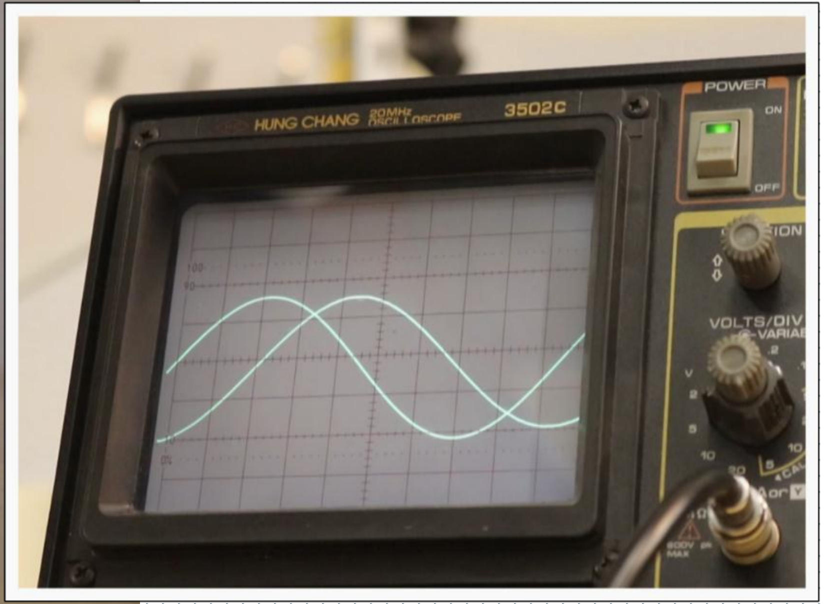


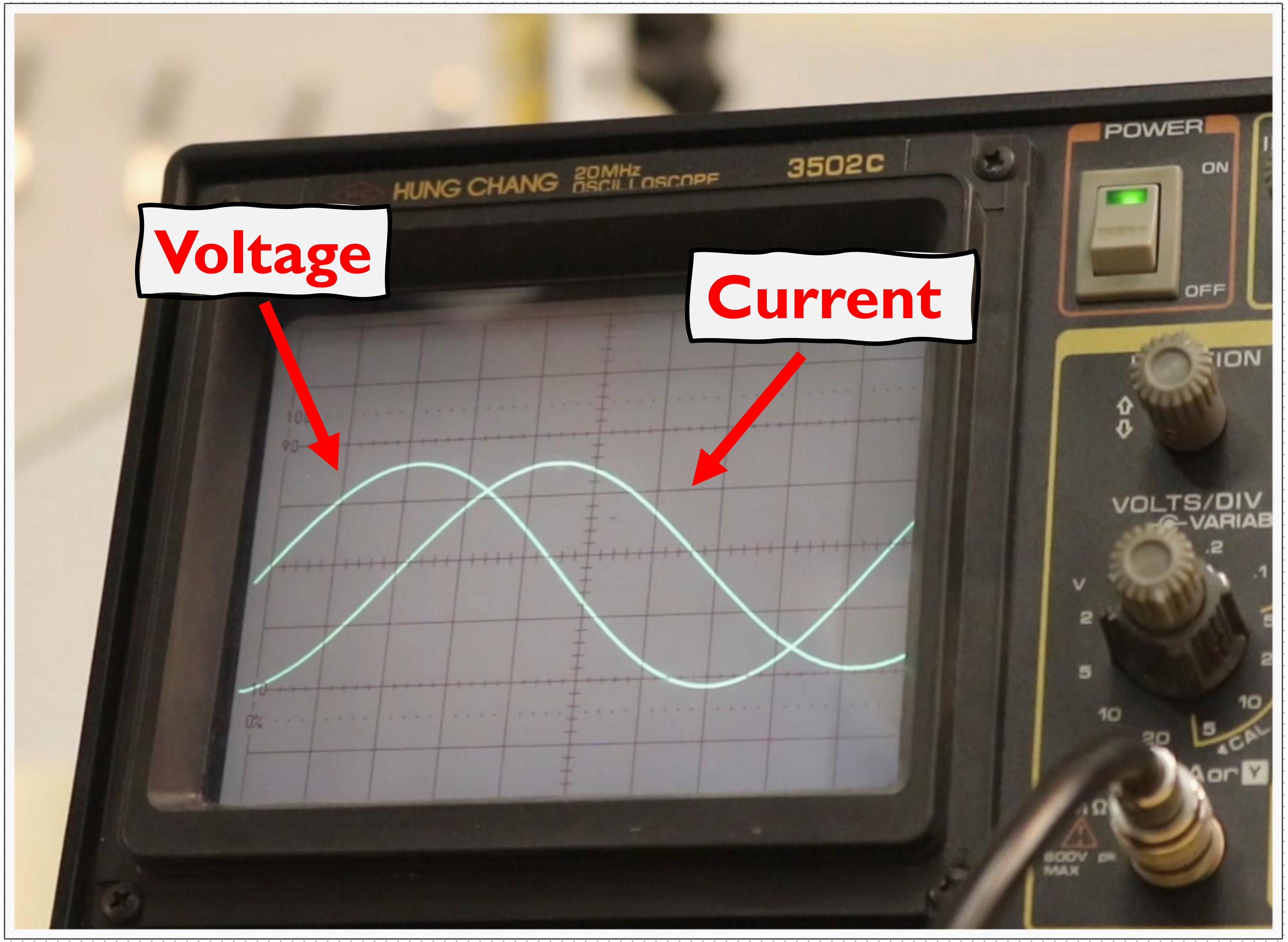




DEMONSTRATION



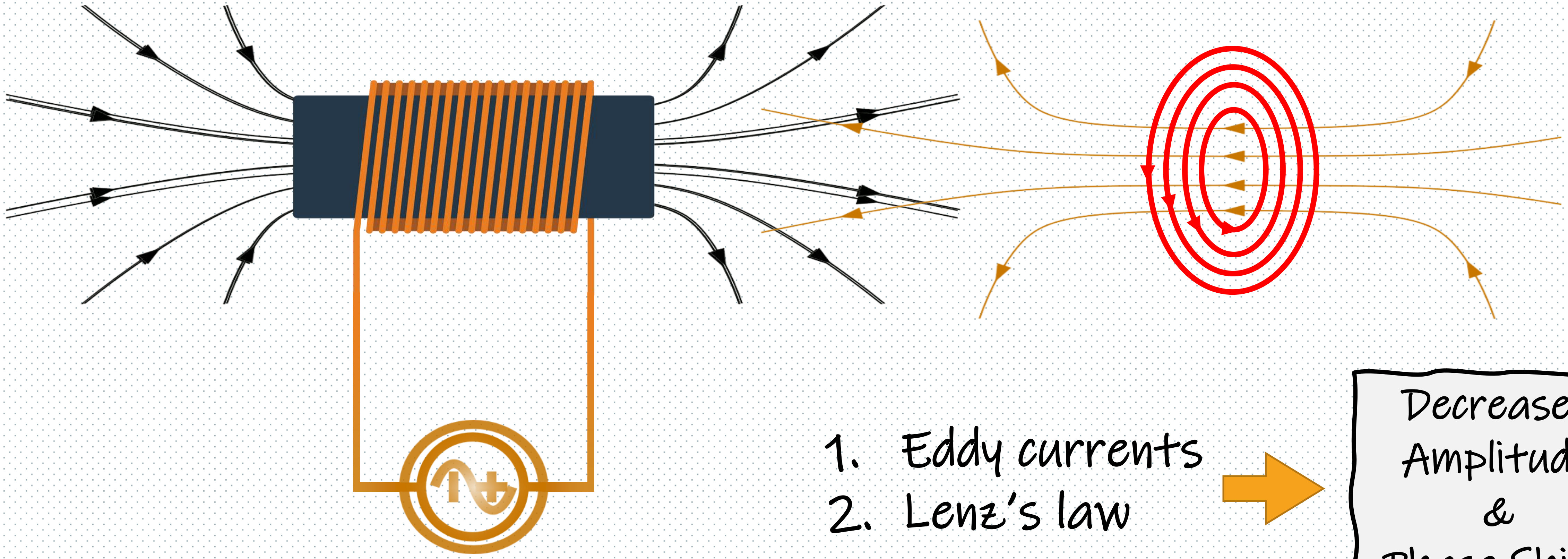




Voltage
Current
HUNG CHANG
20MHz
OSCILLOSCOPE
3502C
POWER
ON
OFF
VOLTS/DIV

BASIC EXPLANATION

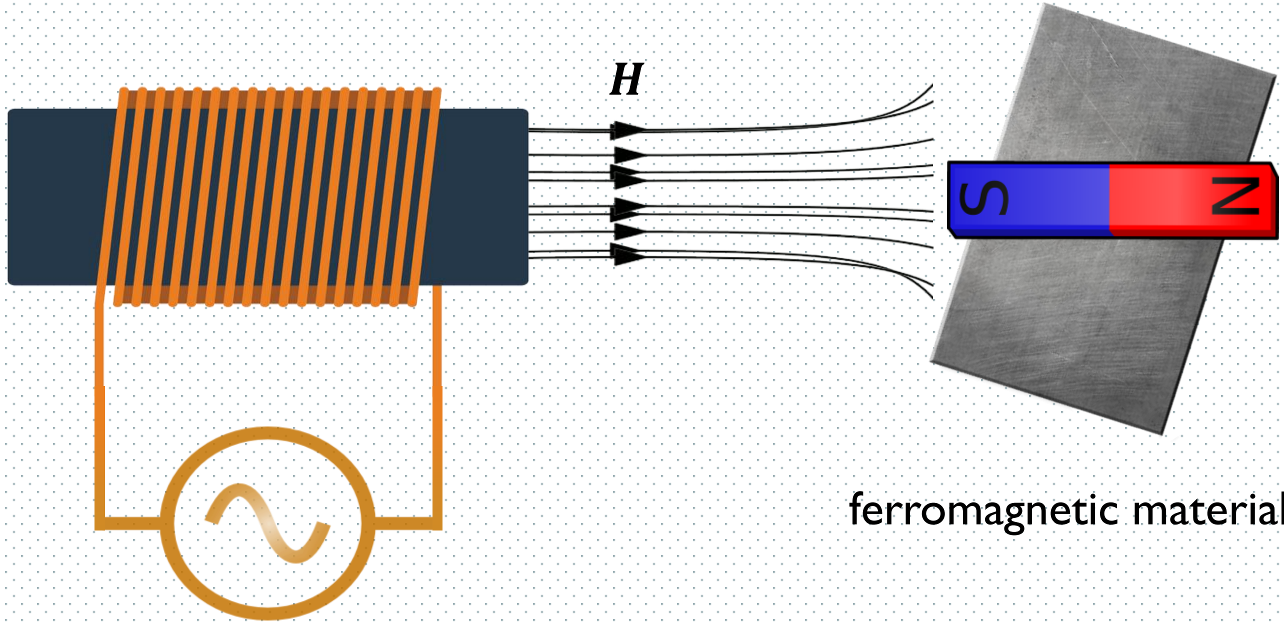
I. effect – **Eddy currents**



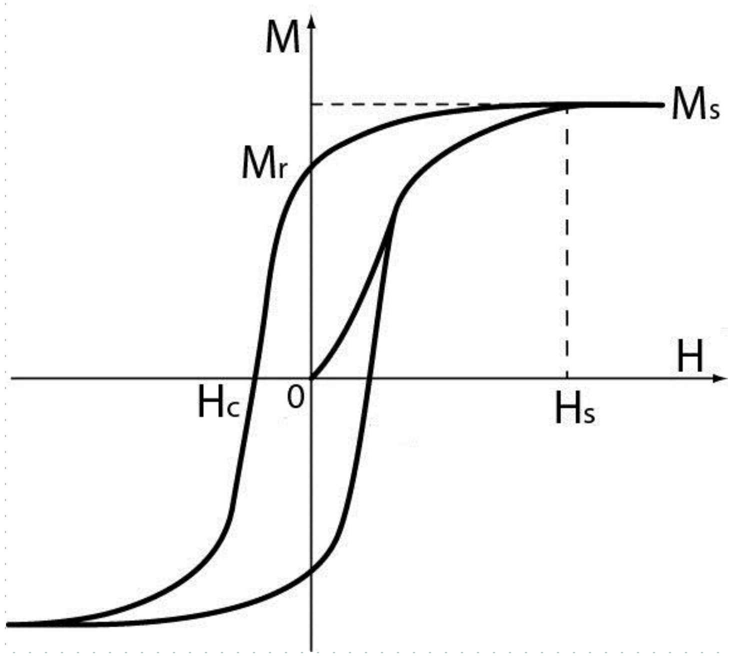
1. Eddy currents
2. Lenz's law

Decreased Amplitude & Phase Shift

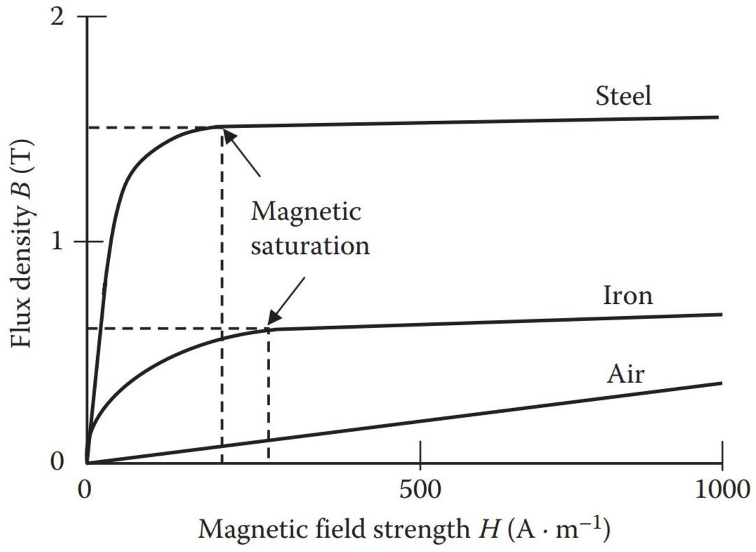
II. effect - **Magnetization** of the ferromagnetic material



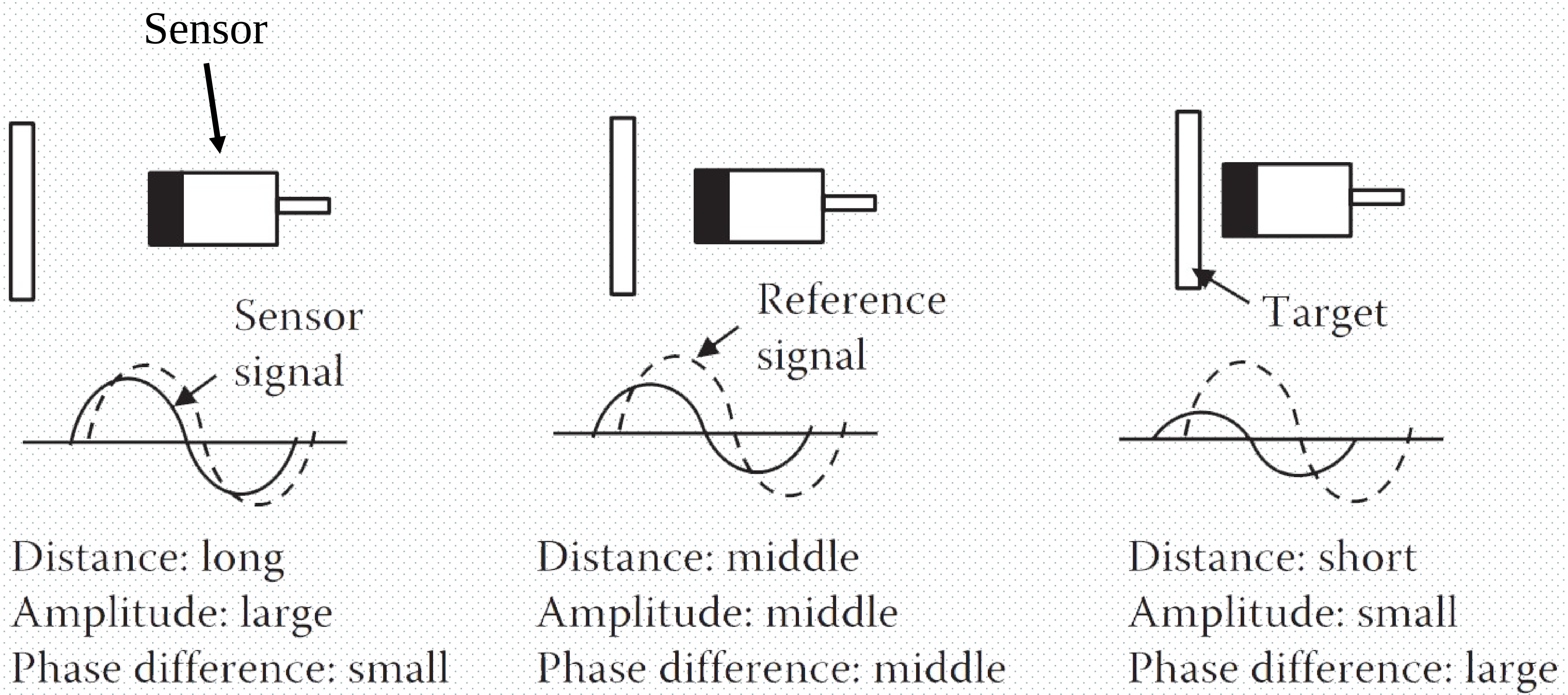
ferromagnetic material



Hysteresis loop of magnetization



Φ increases ➡ $L = \dfrac{\Phi}{I}$ increases ➡ **frequency decreases**


Sensor
Sensor signal
Reference signal
Target
Distance: long
Amplitude: large
Phase difference: small
Distance: middle
Amplitude: middle
Phase difference: middle
Distance: short
Amplitude: small
Phase difference: large

POSSIBLE THEORETICAL CONSIDERATIONS

I., Using **power dissipation of Eddy currents**

$$P = \frac{\pi^2 B^2 d^2 f^2 V}{6\rho k}$$ [I]

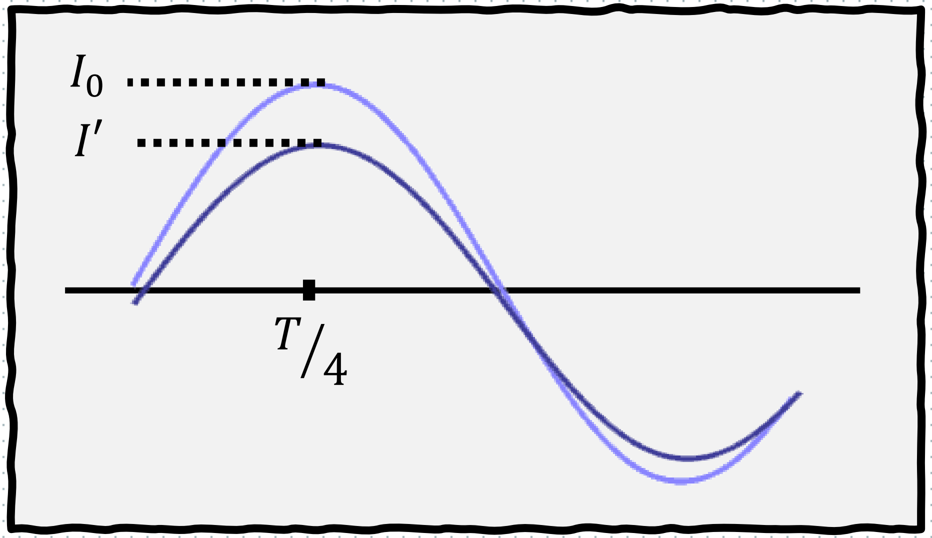
P is the power lost (W),
B is the peak magnetic field (T),
d is the thickness of the sheet or diameter of the wire (m),
f is the frequency (Hz),
k is a constant (1 - thin sheet, 2 - thin wire)
ρ is the resistivity of the material (Ω m)
V is the volume of the material (kg/m3).

[I] F. Fiorillo, *Measurement and Characterization of Magnetic Materials*, Elsevier Academic Press, 2004, p. 31

The **voltage** and **current** of the inductor: $U(t) = U_0 \cdot \sin \omega t \quad I(t) = I_0 \cdot \cos \omega t$

$$P = \frac{\pi^2 B^2 d^2 f^2 V}{6\rho k} = c_1 \cdot B^2 = c_1 \cdot c_2 \cdot I_0^2 \cdot \cos^2(\omega t)$$

c_2 depends on the distance of the target! $c_2(d)$



Energy loss due to eddy currents in a quarter cycle:

$$W_{loss} = \frac{\pi c_1 c_2}{4\omega} \cdot I_0^2 = K \cdot I_0^2$$

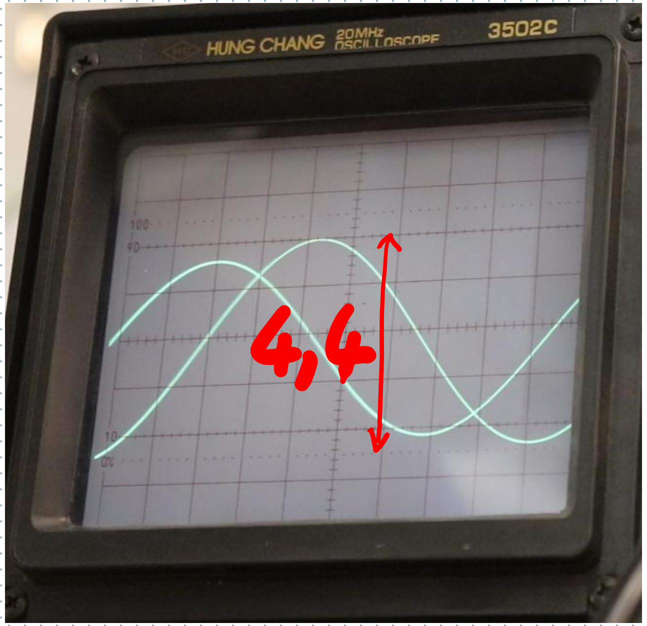
K depends on the distance of the target! $K(d)$

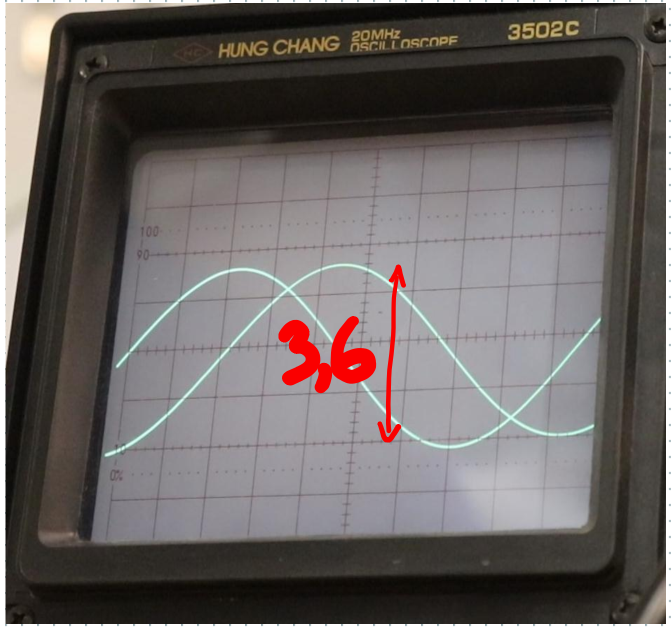
Inductor's change of energy:

$$\Delta W_{ind} = W_0 - W' = \frac{1}{2} L I_0^2 - \frac{1}{2} L I'^2 = \frac{1}{2} L (I_0^2 - I'^2)$$

$$W_{loss} = \Delta W_{ind} = \frac{1}{2} L (I_0^2 - I'^2) = K \cdot I_0^2$$

$$\boxed{\frac{I'}{I_0} = \sqrt{1 - \frac{\pi c_1 c_2}{2L\omega}}}$$





Measured decrease:

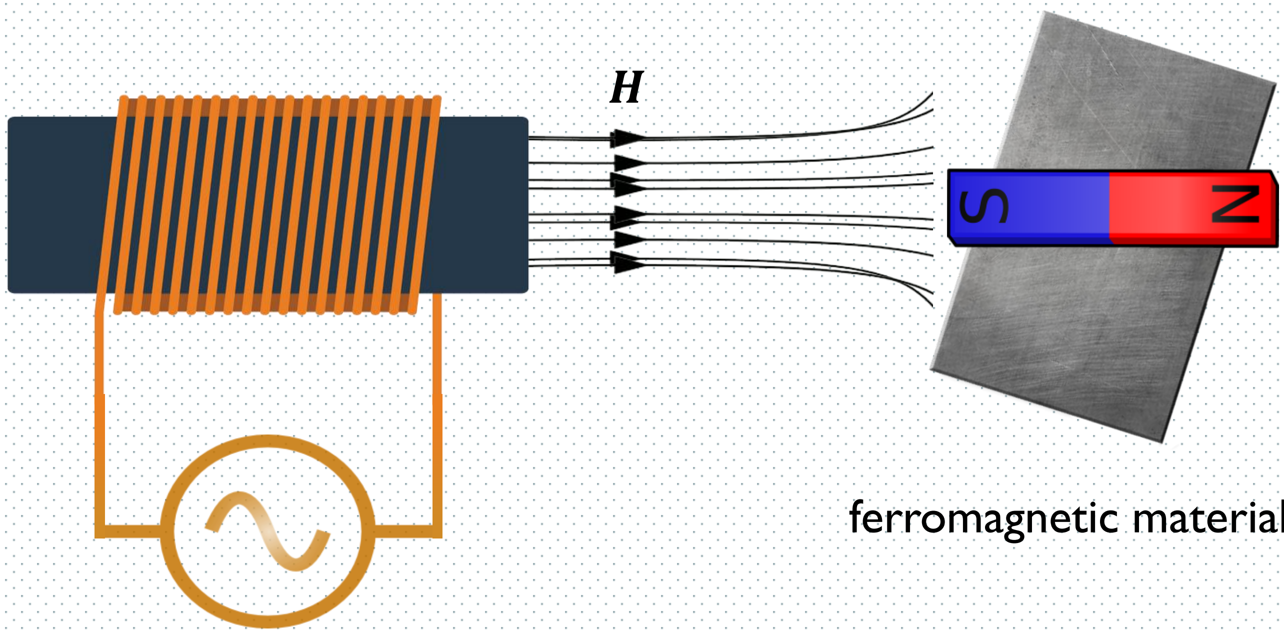
$$\frac{I_1}{I_0} = \frac{3.6}{4.4} = 0.82 \pm 0.08$$

Theoretical:

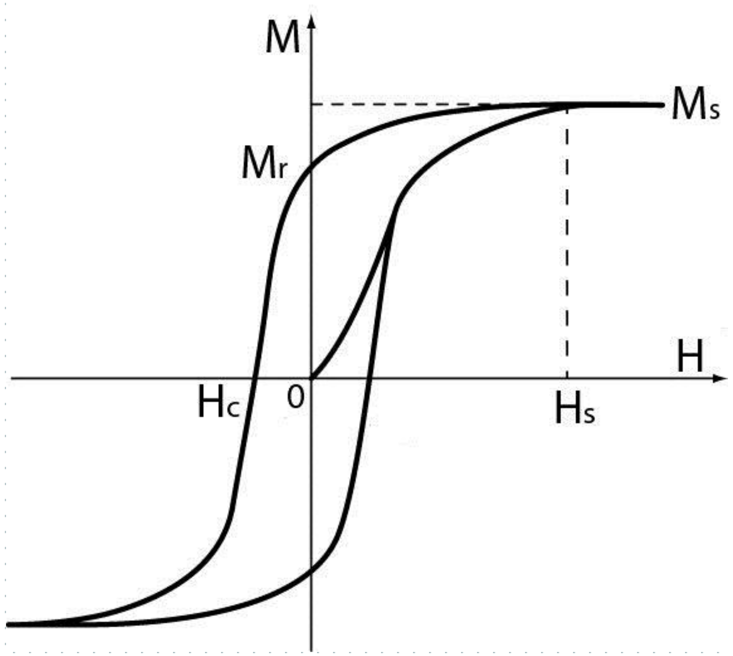
$$\frac{I_1}{I_0} = \sqrt{1 - \frac{\pi c_1 c_2}{2L\omega}} = \sqrt{1 - \frac{\pi^2 d^2 f V \mu_0 \mu_r n}{24 k \rho L}} = 0.966$$

$d \to 0.01\, m, f \to 100 \frac{1}{s}, V \to 0.06 \cdot 0.02 \cdot 0.01 m^3, \rho \to 9.7 \cdot 10^{-8} \Omega m, k \to 1, L \to 4.5\ \mathrm{H}, \mu_r \to 50,$
$\mathrm{N} \to 1200,$

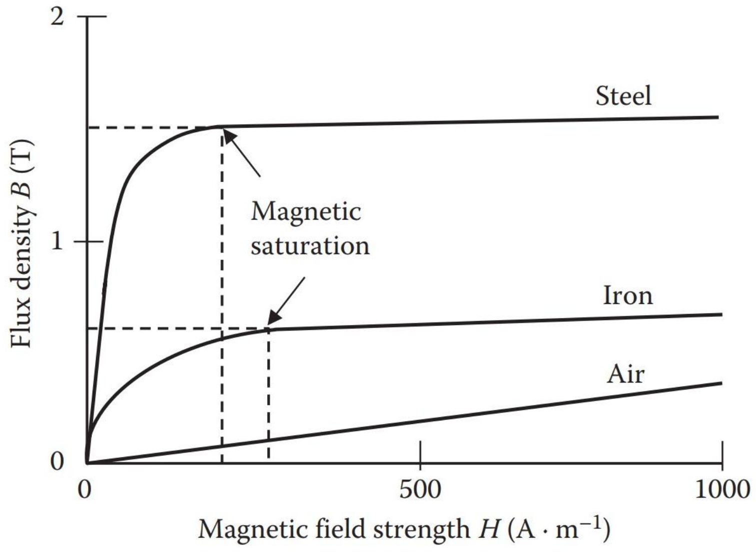
II., Change of inductance



ferromagnetic material



Hysteresis loop of magnetization



Φ increases ➡ $L = \dfrac{\Phi}{I}$ increases ➡ **frequency decreases**

Magnetic field strength at the end of a solenoid:

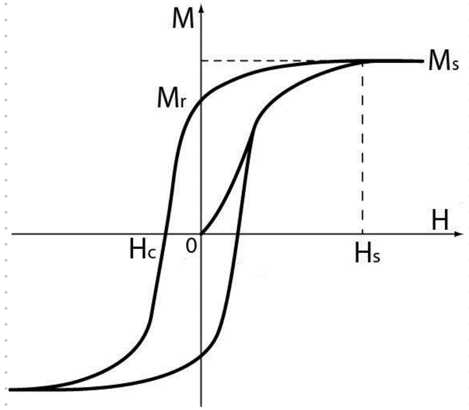
$$H = \frac{IN}{l} \cdot \frac{l}{2\sqrt{r^2 + l^2}}$$

$$B_{\mathrm{magnet}}$$

$$\Delta\Phi = \mathrm{N} \int B_{\mathrm{magnet}} \, dA$$

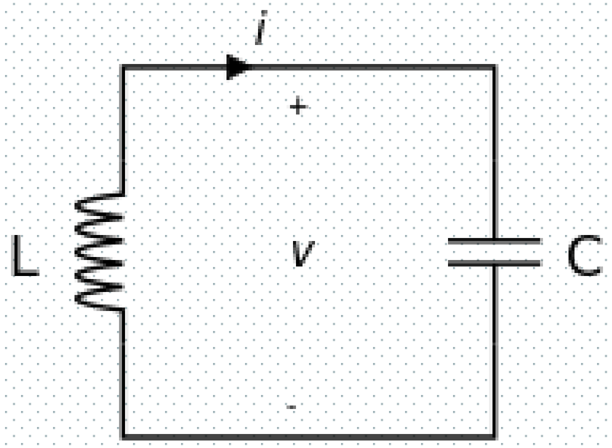
magnetic flux change inside the solenoid

M magnetization



$$L = \frac{\Phi + \Delta\Phi(d)}{I} = \frac{\mu N^2 A}{l} + \frac{\Delta\Phi}{\mathrm{I}} = \mathrm{L}_0 + \frac{\Delta\Phi}{\mathrm{I}}$$

LC circuit:

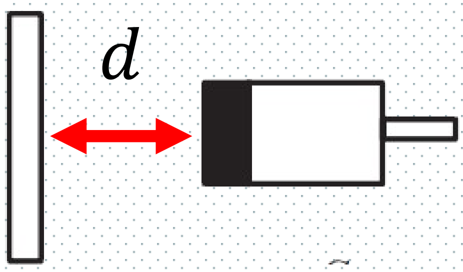


$$L = \mathrm{L}_0 + \frac{\Delta\Phi}{\mathrm{I}}$$

$$\omega = \sqrt{1/_{LC}} = \sqrt{\frac{1}{C(\mathrm{L}_0 + \frac{\Delta\Phi}{\mathrm{I}})}} < \omega_0$$

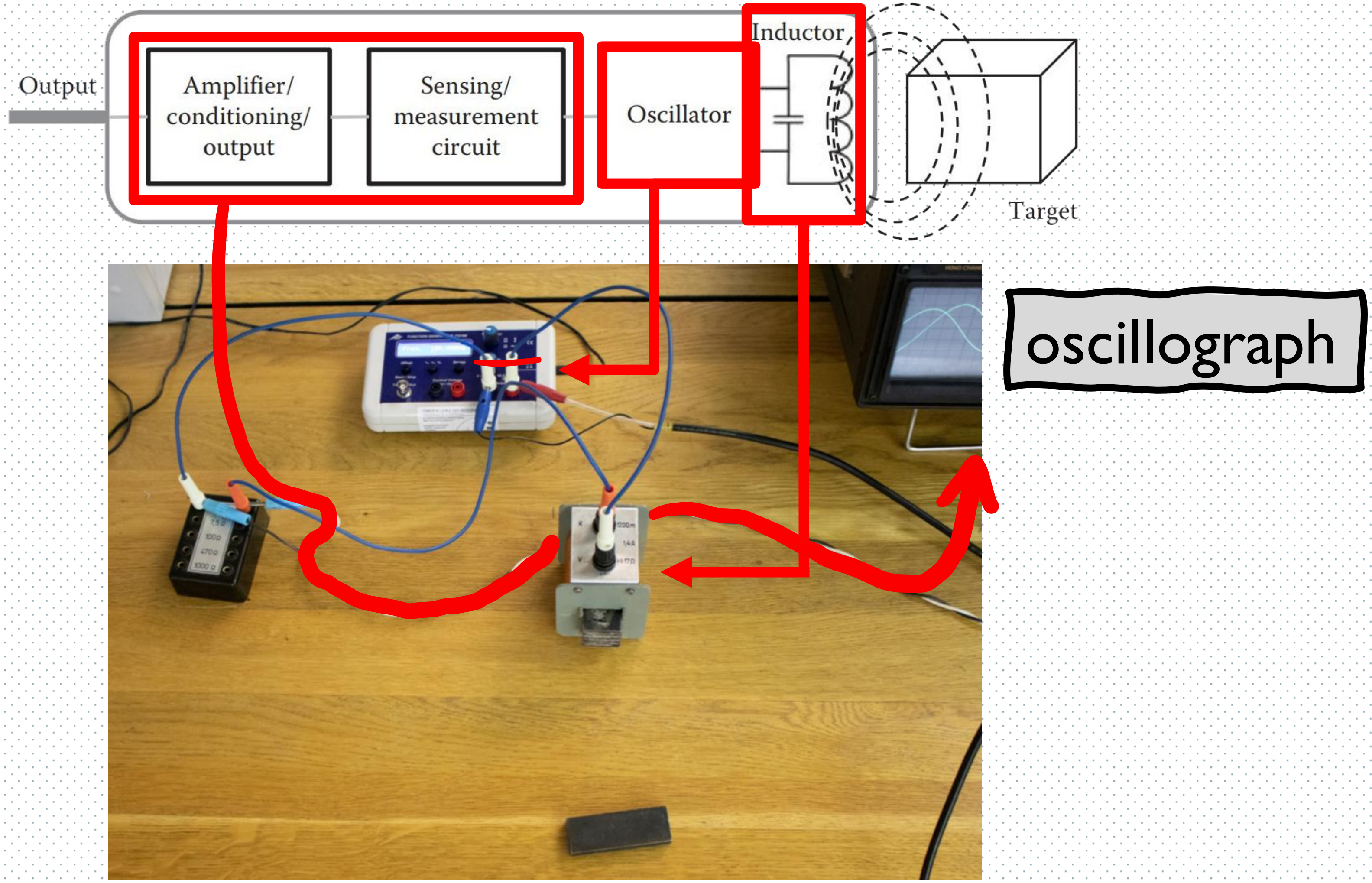
$\Delta\Phi$ is dependent on the distance of the subject (d)!

$$\mathrm{d}_1 < \mathrm{d}_2 \rightarrow \Delta\Phi_1 > \Delta\Phi_1$$



Given the $\delta\omega$ (the **precision** of the measuring device) a formula for **sensing range** can be calculated.

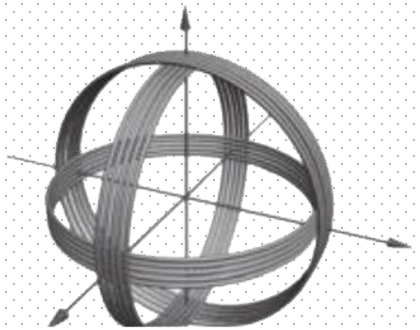
SETUP


Output
Amplifier/ conditioning/ output
Sensing/ measurement circuit
Oscillator
Inductor
Target
oscillograph

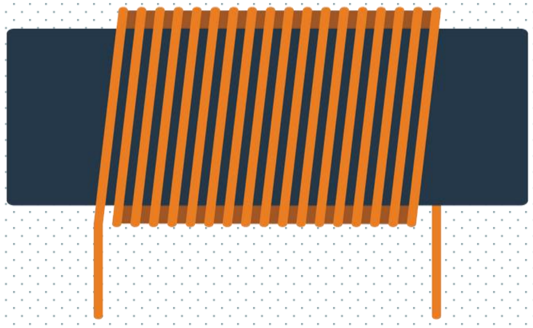
Air Coil
+ light, stable, durable
+ no hysteresis loss
- limited sensitivity (low inductance)

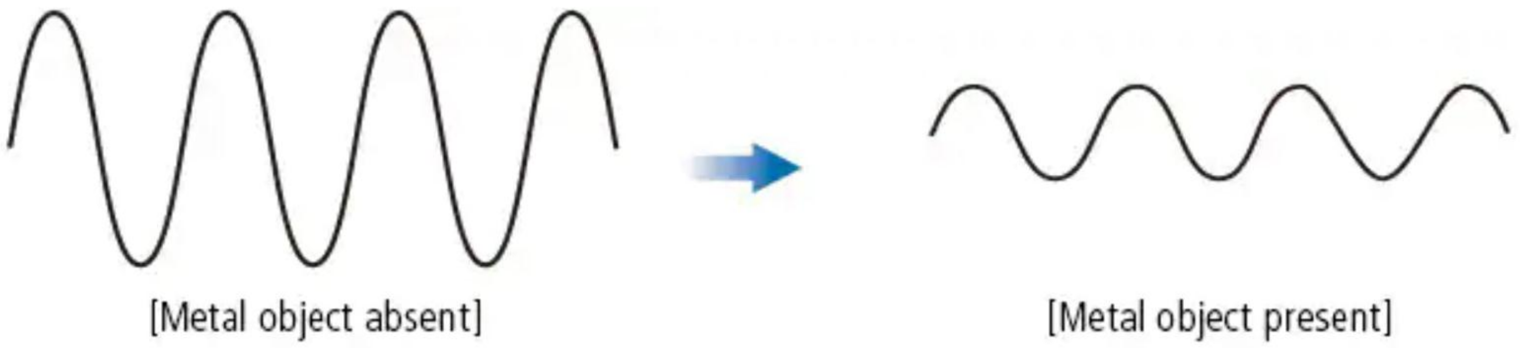
Ferromagnetic core
+ higher sensitivity
- less stable, nonlinear
- more energy loss

Single-coil sensor



Three mutually perpendicular coils





Measuring frequency (f) → reaches threshold value → LED turns on

SOURCES, REFERENCES

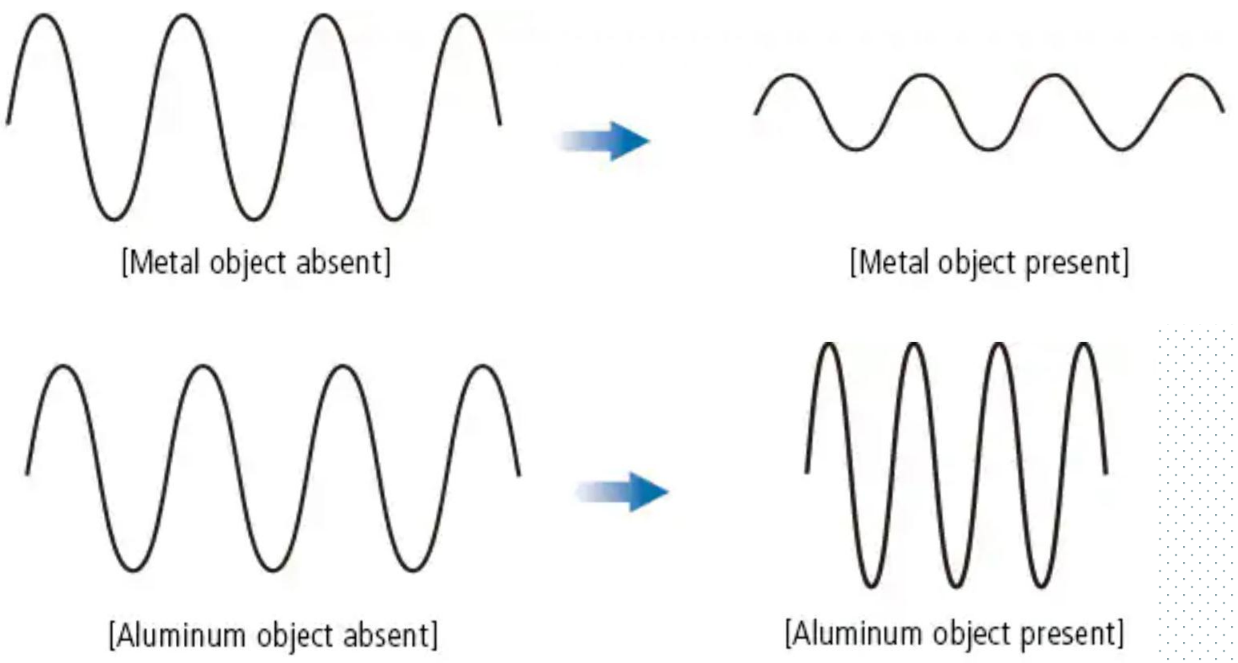
- Winncy Y. Du, *Resistive, Capacitive, Inductive, and Magnetic Sensor Technologies*, Chapter 4 *Inductive Sensors*

- What is an Inductive Proximity Sensor? (available at: https://www.keyence.com/ss/products/sensor/sensorbasics/proximity/info/)

- S. Tumanski, Induction Coil Sensors (available at: http://www.tumanski.x.pl/coil.pdf)

- Griffiths D. J., *Introduction to Electrodynamics*, Cambridge University Press, 2017.

THANK YOU FOR YOUR ATTENTION.



Magnetism	Strong ← Weak		
Detecting distance of general-purpose model	Long ← Short		
Detecting distance of aluminum detection model	Short → Long		
Typical metal	Iron/SUS440	SUS304*	Aluminum/brass/copper

* SUS304 has an intermediate property.

Figures from www.keyence.com (available at: https://www.keyence.com/ss/products/sensor/sensorbasics/proximity/info/)

The **voltage** and **current** of the inductor: $U(t) = U_0 \cdot \sin \omega t \quad I(t) = I_0 \cdot \cos \omega t$

$$P = \frac{\pi^2 B^2 d^2 f^2 V}{6\rho k} = c_1 \cdot B^2 = c_1 \cdot c_2 \cdot I_0^2 \cdot \cos^2(\omega t)$$

Energy loss due to eddy currents in a quater cycle:

$$W_{\frac{1}{4}loss} = \int_{-\frac{\pi}{2\omega}}^{0} P \cdot dt = c_1 \cdot c_2 \cdot I_0^2 \int_{-\frac{\pi}{2\omega}}^{0} \cos^2(\omega t) \cdot dt = \frac{\pi c_1 c_2}{4\omega} \cdot I_0^2$$

Inductor's change of energy meanwhile:

$$\Delta W_{ind} = \frac{1}{2} L I_1^2 = \frac{1}{2} L I_0^2 - W_{\frac{1}{4}loss} = I_0^2 (\frac{1}{2} L - \frac{\pi c_1 c_2}{4\omega})$$

$$\frac{I_1}{I_0} = \sqrt{1 - \frac{\pi c_1 c_2}{2L\omega}}$$