# Non-Destructive Testing (NDT)

## Contrôles Non-Destructifs (CND)

Prof. Antoine Guitton[1]

[1]Université de Lorraine – CNRS – Arts et Métiers – LEM3, Metz, France

2025 – 2026

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**Non-Destructive Testing (NDT)**                                                                                                                           1 / 74

1. General information

2. Background on NDT

3. Some examples of common NDT

4. Some examples of less-common NDT

**1** General information

**2** Background on NDT

**3** Some examples of common NDT

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## Disclaimer

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    Why? $\Rightarrow$ Because!

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Non-Destructive Testing (NDT)     4 / 74

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  Enjoy! (or not...)

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**Why were 32 out of 56 nuclear reactors shut down in France during the winter of 2022/2023? [1]**



Welds
with
cracks

Pipe bend

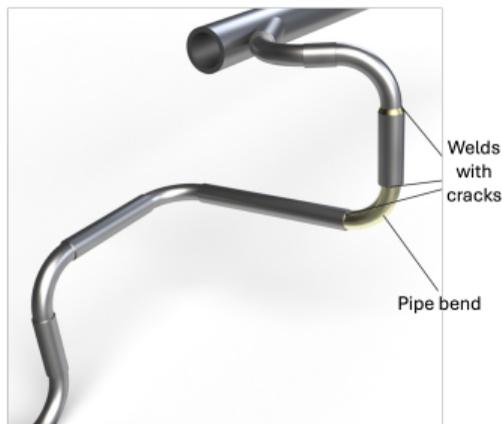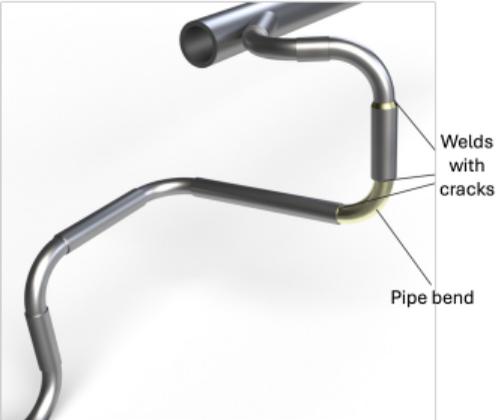- **August 2021:** Unexpected defects found at Civaux reactor 1 during its 10-year inspection.

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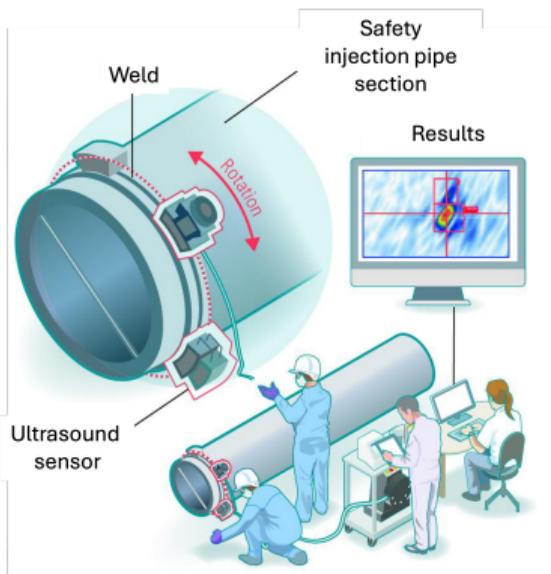
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$\Rightarrow$ **January 2022:** EDF identified similar defects in other reactors, prompting the shutdown of several units.

General information
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Background on NDT
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Some examples of common NDT
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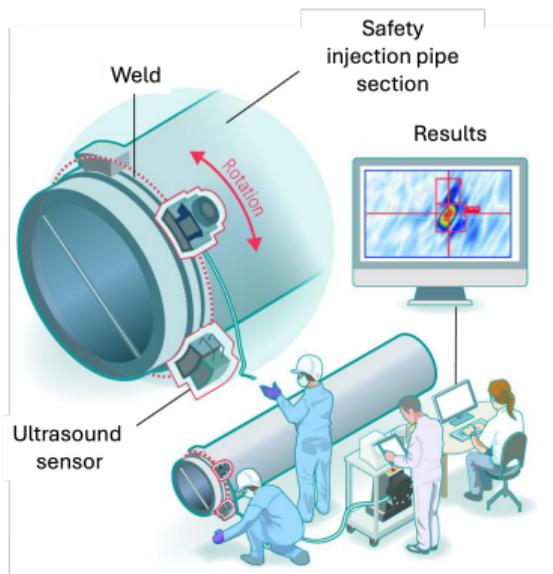
References
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⇒ No need to cut out affected pipe for further analyses

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⇒ **We narrowly avoided a power blackout!**

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**Non-Destructive Testing (NDT)**
8 / 74

## X-rays: A prime example of NDT for medical applications [2]

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⇒ **Since Röntgen did not understand their nature, he called these rays, X-rays!**

⇒ **Medical radiography was born.**

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Non-Destructive Testing (NDT)      9 / 74

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⇒ **Marie Curie and her coworkers developed mobile radiography devices.**

**General principle of NDT**

Excitation

Electromagnetic wave, mechanical vibration, magnetic field, thermal...

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Electromagnetic wave, mechanical vibration, magnetic field, thermal...

### Perturbation

Anomalies, defects, or variations in structures or properties within the specimen perturb the excitation.

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Non-Destructive Testing (NDT)                                                                                    12 / 74

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### Excitation

Electromagnetic wave, mechanical vibration, magnetic field, thermal…

### Perturbation

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### Revelation

Eyes, sensor, signal, image…

$\Rightarrow$ **Interpreting the results of NDT means understanding the Physics behind it *a bit*…**

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Non-Destructive Testing (NDT)      12 / 74

## Some definitions

### Non-Destructive Testing (NDT)

NDT methods provide insights into the health of components and structures without causing damage that could impair their future use.

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### Objectives of NDT

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### NDT method selection:

Analyze defect severity, progression over time, and failure mechanics. Choose methods based on required sensitivity and detection limits.

**Some definitions**

Stages in the NDT inspection process of a specimen

NDT can be performed at various stages of a component's lifecycle:

- **Raw Materials:** NDT can be employed on raw materials to detect defects or inconsistencies before they enter the manufacturing process.

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- **In-Service:** NDT can be conducted on in-service components to assess their condition, detect potential damage, and ensure continued safe operation.

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**Non-Destructive Testing (NDT)**       14 / 74

**Few words on certifications**

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The COFREND certification

- 3 levels of expertise
- 1 certification for each NDT technique and each industrial sector

**1** General information

**2** Background on NDT
    Introduction to NDT
    What are NDT?
    Defects and some orders of magnitude

**3** Some examples of common NDT

**4** Some examples of less-common NDT

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**Non-Destructive Testing (NDT)**      16 / 74

**Defects and some orders of magnitude I**

Millimeter scale $1\,\text{mm} = 10^{-3}\,\text{m}$

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**Families of defects**

### Open defects

- **Surface defects** are located on the surface of the material. They can be caused by factors such as manufacturing, wear, or corrosion. Common types of surface defects include cracks, scratches, pores, and burrs.

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Volume defects

These defects are located inside the material.

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**2** Background on NDT

**3** Some examples of common NDT
  Visual testing (VT)
  Dye penetrant inspection (DPI)
  Magnetic particle inspection (MPI)
  Ultrasonic testing (UST)

**4** Some examples of less-common NDT

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**Non-Destructive Testing (NDT)**                                                                21 / 74

**Principle of visual testing (VT)**

Definition

VT involves a close surface inspection for integrity-threatening defects, following set standards [4].

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References
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## Principle of visual testing (VT)

### Definition

VT involves a close surface inspection for integrity-threatening defects, following set standards [4].

### Basic principle

VT relies on the human eye, with or without magnification and lighting, to spot surface defects by analyzing variations in texture, color, and gloss.

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Some examples of less-common NDT
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References
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**Principle of visual testing (VT)**

### Definition

VT involves a close surface inspection for integrity-threatening
defects, following set standards [4].

### Basic principle

VT relies on the human eye, with or without magnification and
lighting, to spot surface defects by analyzing variations in texture,
color, and gloss.



### Pros/Cons

- **Pros:** simplicity, speed, low cost, applicable to a wide range of situations...
- **Cons:** surface only, subjectivity, good visual acuity and proper training...

**A few words on the physics behind it**



### Resolution: Airy disk and Rayleigh criterion

It refers to the ability to distinguish between very close details.
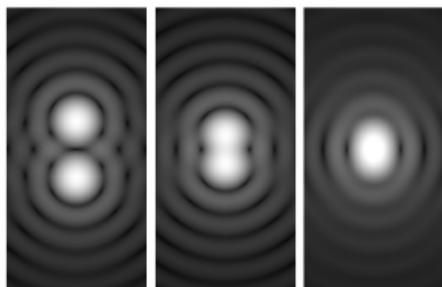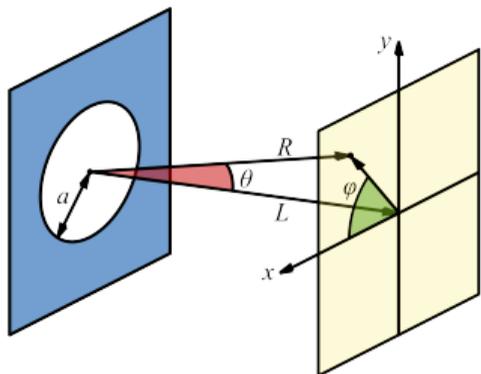
$$I(\theta) = I_0 \left( \frac{J_1(ka\sin\theta)}{ka\sin\theta} \right)^2 \; ; \; k = \frac{2\pi}{\lambda}$$

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The first dark ring is at:
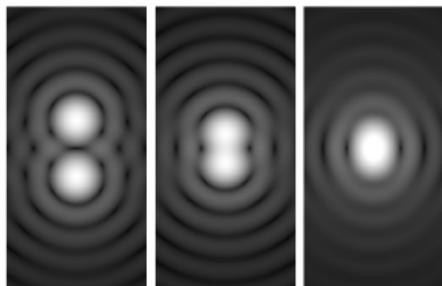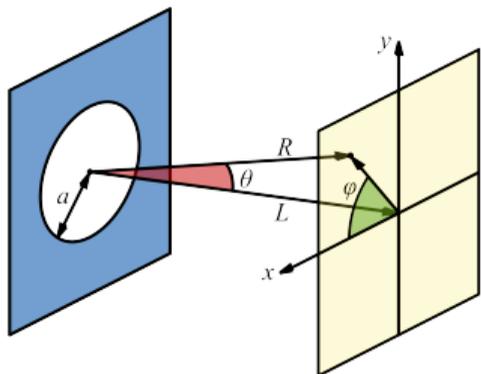
$$\sin \theta = 0.61 \frac{\lambda}{a} \approx \theta$$

**A few words on the physics behind it**



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It refers to the ability to distinguish between very close details.

$$I(\theta) = I_0 \left( \frac{J_1(ka\sin\theta)}{ka\sin\theta} \right)^2 ; k = \frac{2\pi}{\lambda}$$

The first dark ring is at:

$$\sin\theta = 0.61\frac{\lambda}{a} \approx \theta$$

The 1st minimum coincides with the maximum of the other.

$$\Rightarrow \Delta r = L\tan\left( 0.61\frac{\lambda}{a} \right) \approx 0.61\frac{\lambda}{a}L$$

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Non-Destructive Testing (NDT)     24 / 74

**1** General information

**2** Background on NDT

**3** Some examples of common NDT
Visual testing (VT)
Dye penetrant inspection (DPI)
Magnetic particle inspection (MPI)
Ultrasonic testing (UST)

**4** Some examples of less-common NDT

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Non-Destructive Testing (NDT) — 25 / 74

**Principle of dye penetrant inspection (DPI) [5]**

Definition

DPI involves applying a liquid to highlight open discontinuities on the specimen.

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Non-Destructive Testing (NDT)                                                                                26 / 74

**Principle of dye penetrant inspection (DPI) [5]**

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Basic principle

DPI is based on capillary forces and wettability, where a low surface tension fluid penetrates surface-breaking discontinuities. Then, the excess penetrant is removed and a developer is applied.

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### Pros/Cons

- **Pros:** simplicity, speed, low cost, applicable to a wide range of situations...
- **Cons:** surface only, surface precleaning, Chemical handling...

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**Non-Destructive Testing (NDT)**     26 / 74

**A few words on the physics behind it I**

Surface tension

It is defined as the force existing at the surface of a liquid due to the attraction between molecules, which resists the rupture of the surface.

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Non-Destructive Testing (NDT)                                                                                          27 / 74

**A few words on the physics behind it I**

### Surface tension

It is defined as the force existing at the surface of a liquid due to the attraction between molecules, which resists the rupture of the surface.

### Wettability

It is a measure of how easily a liquid spreads across or adheres to a surface and is influenced by the surface's chemical and physical properties.

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It is a measure of how easily a liquid spreads across or adheres to a surface and is influenced by the surface's chemical and physical properties.

$$h = \frac{4\gamma \cos \alpha}{d\rho g}$$

### Capillary

It is the ability of a liquid to flow in narrow spaces without the assistance of, and often in opposition to, external forces like gravity.

**A few words on the physics behind it II**

DPI can operate under fluorescence. Ultraviolet light excites the penetrant, emitting visible green light ($\lambda = 550\,\mathrm{nm}$) where our eyes are most sensitive.

Luminescence

Emission of light by a substance not resulting from heat.
There are several types of luminescence.

General information
oo
Background on NDT
oooooooooooooooooo
Some examples of common NDT
ooooooo●ooooooooooooooooo
Some examples of less-common NDT
oooooooooooooooooooooooooooooo
References
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## A few words on the physics behind it II

DPI can operate under fluorescence. Ultraviolet light excites the penetrant, emitting visible green light ($\lambda = 550\,\text{nm}$) where our eyes are most sensitive.

### Luminescence

Emission of light by a substance not resulting from heat. There are several types of luminescence.

### Fluorescence

It is defined as the emission of light that ends immediately after the source of excitation is removed.

### Phosphorescence

It is defined as persistent emission of light after the end of excitation.

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**Principle of magnetic particle inspection (MPI) I [6]**

Definition

MPI consists of detecting defects in ferromagnetic materials by applying a magnetic field and using an indicator substance.

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### Basic principle

Defects distort the field, creating a magnetic leakage field. An indicator substance is applied during or after magnetization and is attracted to defects by magnetic forces, forming visible indications.

**Principle of magnetic particle inspection (MPI) I [6]**

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**Non-Destructive Testing (NDT)**      30 / 74

**Principle of magnetic particle inspection (MPI) I [6]**

### Definition

MPI consists of detecting defects in ferromagnetic materials by applying a magnetic field and using an indicator substance.

### Basic principle

Defects distort the field, creating a magnetic leakage field. An indicator substance is applied during or after magnetization and is attracted to defects by magnetic forces, forming visible indications.

### Pros/Cons

- **Pros:** simplicity, speed, low cost, surface and near-surface defects…
- **Cons:** surface precleaning, limited to ferromagnetic, chemical handling. …

**Principle of magnetic particle inspection (MPI) II [6]**

Various details

- Magnetization is "longitudinal" when applied parallel to the piece's greatest length or axis, and "transverse" when applied perpendicular.
- Longitudinal magnetization detects transverse defects; transverse magnetization detects longitudinal defects.

Longitudinal magnetization



Transversal magnetization

**Principle of magnetic particle inspection (MPI) II [6]**

Various details

Longitudinal magnetization



Transversal magnetization



- Magnetization is "longitudinal" when applied parallel to the piece's greatest length or axis, and "transverse" when applied perpendicular.

- Longitudinal magnetization detects transverse defects; transverse magnetization detects longitudinal defects.

  - AC fields detect surface defects; DC fields detect subsurface defects.

 ⇒ Skin effect: electromagnetic phenomenon causing high-frequency currents to flow only on the surface of conductors: ($f$: frequency; $\sigma$: electrical conductivity; $\mu$: magnetic permeability)

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$$

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Non-Destructive Testing (NDT)      31 / 74

**A few words on the physics behind it I**

Magnetic field (*H*)

*H* is the applied magnetic field, generated by external sources. Unit: $\text{A m}^{-1}$

**A few words on the physics behind it I**

Magnetic field (**H**)

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Magnetization field (**M**)

**M** represents the material's internal response to **H**. Unit: $A\,m^{-1}$

$$\boldsymbol{M} = \chi_m \boldsymbol{H} \quad \text{where } \chi_m \text{ is the magnetic susceptibility.}$$

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Magnetic field ($H$)

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$M$ represents the material's internal response to $H$. Unit: $A\,m^{-1}$

$$M = \chi_m H \quad \text{where } \chi_m \text{ is the magnetic susceptibility.}$$

Total induced magnetic field ($B$)

$B$ is the total induced magnetic field. Unit: T.

$$B = \mu_0 \left( H + M \right) \quad \text{where } \mu_0 \text{ is the vacuum permeability.}$$

**A few words on the physics behind it II**

$\boldsymbol{H} = 0$

Unmagnetized ferromagnetic materials ($\chi_m \gg 1$) have tiny magnetic regions (Weiss domains) acting like random miniature magnets. This cancels out their overall magnetic field ($\boldsymbol{B} = 0$).

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**Non-Destructive Testing (NDT)**                                                                              33 / 74

## A few words on the physics behind it II

### $H = 0$

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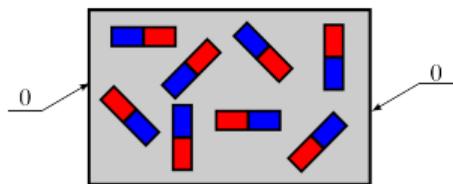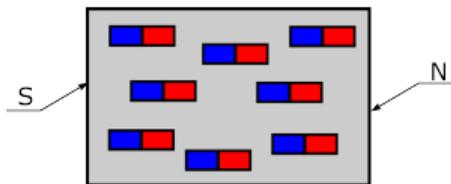
### $H \neq 0$

When it is placed in a magnetic field ($H \neq 0$), all the magnetic moments gradually align parallel to the applied magnetic field. Once all the magnetic moments are aligned, a magnetic induction called "saturation magnetic induction" ($B_s$) is reached.

**A few words on the physics behind it III**

**$H = 0$**

Reducing the magnetic field ($H$) to zero doesn't fully reset the material. A remaining magnetic field exists, called "remanent magnetic induction" ($B_r$).

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**Non-Destructive Testing (NDT)**     34 / 74

**A few words on the physics behind it III**

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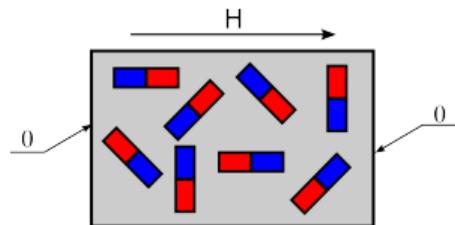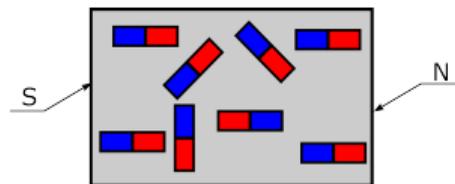




### $-H$

It is then possible to apply a magnetic field of opposite direction $-H$. The value of the magnetic field that again allows to obtain a zero magnetic induction ($B = 0$) within the material is called "coercive field" ($H_C$).

**A few words on the physics behind it IV**

## Hysteresis loop

- In a magnetic field ($H > 0$), magnetic moments align with the field. Once fully aligned, "saturation magnetic induction" ($B_s$) is achieved.

- Reducing the magnetic field ($H$) to zero doesn't fully reset the material. A remaining magnetic field exists ($B_r$).

- It is then possible to apply a magnetic field of opposite direction $-H_C$ to obtain a zero magnetic induction ($B = 0$).

⇒ Applying an opposing magnetic field until saturation and then reversing it creates a characteristic "hysteresis loop".

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Non-Destructive Testing (NDT) — 35 / 74

**A few words on the physics behind it V**

Leakage magnetic field near a defect [6]

Very complicated. There is a lot of literature...

Field line

They are the set of curves that are tangent to the field at every point.

$$\boldsymbol{B} \times \boldsymbol{dl} = 0$$

Magnetic attraction force on a ferromagnetic particle of a volume $V$ [7]

$$\boldsymbol{F} = \chi_m V \boldsymbol{B} \nabla(\boldsymbol{B})$$
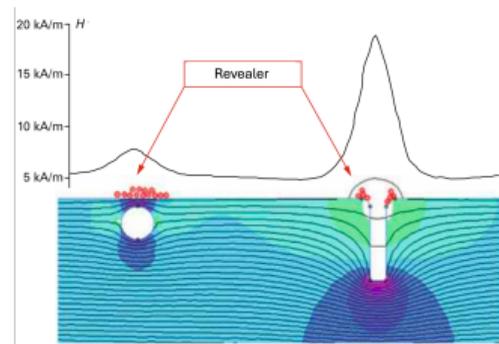
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**Non-Destructive Testing (NDT)**      37 / 74

# Principle of ultrasonic testing (UST)

## Basic principle

UST uses high-frequency sound waves transmitted through a coupling medium to inspect materials internally without damage. By measuring reflected echoes, it detects defects and thickness variations, revealing structural details and defects.
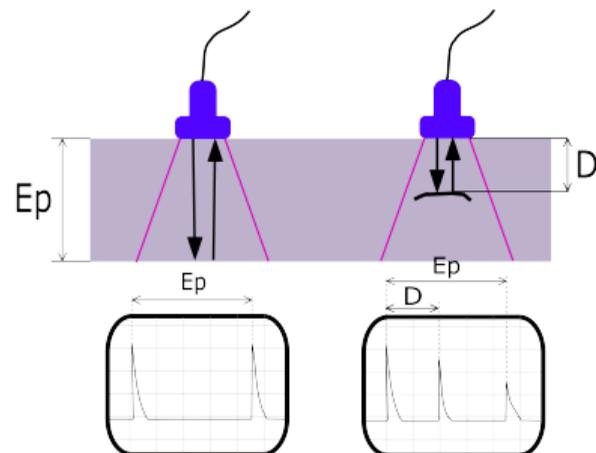
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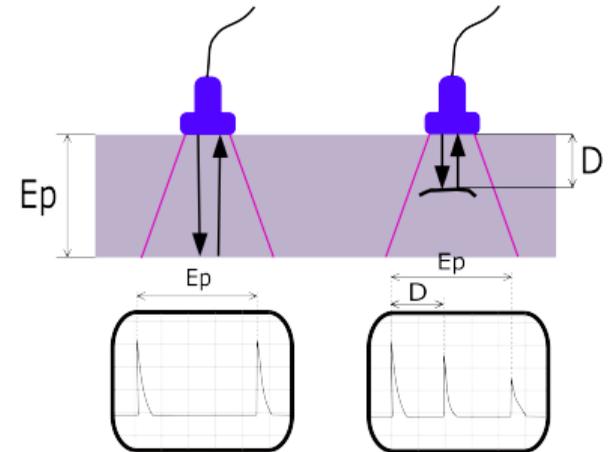


## Pros/Cons

- **Pros:** High sensitivity, depth penetration, versatility, real-time, portability…
- **Cons:** Surface preparation, operator skill, equipment cost, geometric limitations…

## A few words on the physics behind it I

### Ultrasound (US)

US is defined as sound at frequencies ($f$) greater than $20\,\text{kHz}$. In air at atmospheric pressure, ultrasonic waves have wavelengths ($\lambda$) of $1.9\,\text{cm}$ or less.

$$\lambda = \frac{c}{f} \quad \text{where } c \text{ is the celerity}$$
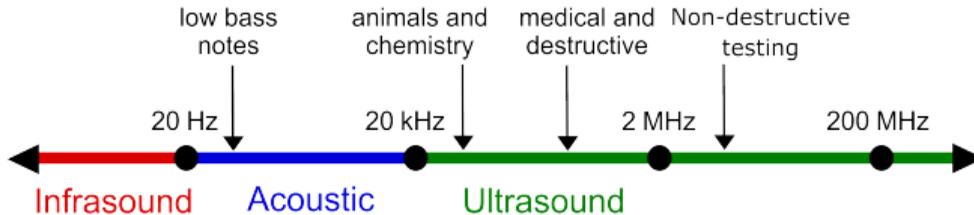
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**Non-Destructive Testing (NDT)**     39 / 74

**A few words on the physics behind it II**

### What is a wave?

A wave arises when the local time disturbance of a physical quantity $\psi$ induces a spatial variation in another quantity $\phi$:

$$\frac{\partial \psi}{\partial t} = a\frac{\partial \phi}{\partial x} \quad ; \quad \frac{\partial \phi}{\partial t} = b\frac{\partial \psi}{\partial x}$$

**A few words on the physics behind it II**

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### Wave propagation: D'Alembert's equation

The combination of these two equations leads to the propagation equation:

$$\frac{\partial^2 \psi}{\partial t^2} = ab\frac{\partial^2 \psi}{\partial x^2} \iff \ddot{\psi} = c^2\Delta\psi$$

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Non-Destructive Testing (NDT) | 40 / 74

## A few words on the physics behind it III

Elastic waves within a material [8]

An ideal elastic wave is a mechanical disturbance that propagates through a material, causing atoms to oscillate around their equilibrium positions without other changes.

**A few words on the physics behind it III**

Elastic waves within a material [8]

An ideal elastic wave is a mechanical disturbance that propagates through a material, causing atoms to oscillate around their equilibrium positions without other changes.

**Propagation of elastic waves within anisotropic materials:**

$$\frac{\partial^2 u_i}{\partial t^2} = \frac{1}{\rho} C_{iklm} \frac{\partial^2 u_m}{\partial x_k \partial x_l}$$ where $\rho$ is the density and $C_{iklm}$ the elastic coefficient tensor

**Propagation of elastic waves within isotropic materials ($E, \nu$):**

$$\frac{\partial^2 u_i}{\partial t^2} = \overbrace{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}^{=c_L^2} \frac{\partial^2 u_i}{\partial x_i^2} + \overbrace{\frac{E}{2\rho(1+\nu)}}^{=c_T^2} \frac{\partial^2 u_i}{\partial x_i \partial x_l}$$

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Non-Destructive Testing (NDT)     41 / 74

**A few words on the physics behind it IV**

### Plane wave

Far from the source, the US wave behaves as a plane wave, which has infinite, parallel wavefronts and propagates in a single direction with constant amplitude and phase.

$$u(\boldsymbol{r}, t) = A\cos\left(\frac{2\pi}{\lambda}\boldsymbol{n} \cdot \boldsymbol{r} - 2\pi f t + \varphi\right)$$

**A few words on the physics behind it IV**

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Propagation



Disturbance
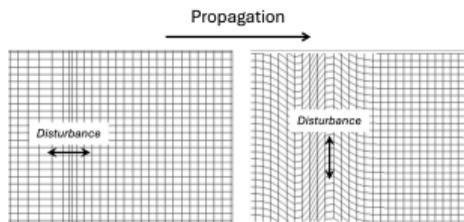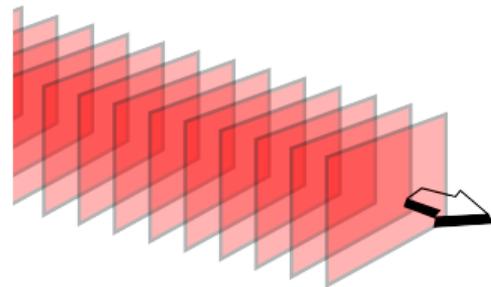
Disturbance

### Longitudinal and transversal waves

A longitudinal wave ($c_L$) has disturbances in the direction of propagation. When the disturbance is orthogonal to the propagation, the wave is transverse ($c_T$).

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Non-Destructive Testing (NDT) — 42 / 74

## Visualization of ultrasonic information

### A-Scan

It shows the amplitude of reflected ultrasound waves over time, providing a one-dimensional view of internal material defects based on echo time delay and amplitude.

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### B-Scan

It creates a 2D cross-sectional view by moving a transducer across the material, showing internal structures and defects based on depth and position.

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It shows the amplitude of reflected ultrasound waves over time, providing a one-dimensional view of internal material defects based on echo time delay and amplitude.

### B-Scan

It creates a 2D cross-sectional view by moving a transducer across the material, showing internal structures and defects based on depth and position.

### C-Scan

It provides a 2D top-down view of internal structures by scanning with a transducer in a grid, recording reflected signals to map defects or features.

**1** General information

**2** Background on NDT

**3** Some examples of common NDT

**4** Some examples of less-common NDT
  Photoelasticity
  Radiography
  Tomography
  Thermography
  Eddy-current testing

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**Non-Destructive Testing (NDT)**                    44 / 74

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**Principle of the photoelasticity**

Basic principle

It reveals stress patterns in transparent materials. Under polarized light, stressed materials show fringes, indicating internal stress distribution for visualization and analysis.

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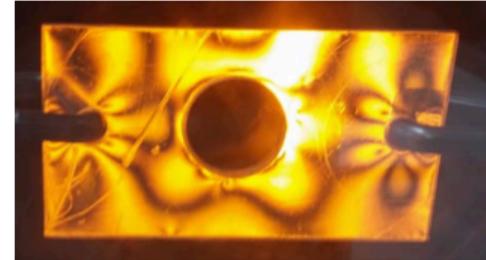


Pros/Cons

- **Pros:** direct visualization of stress distribution, detailed analysis...
- **Cons:** applicable only to transparent materials, setup complexity, primarily qualitative; precise quantitative analysis can be challenging....

**A few words on the physics behind it I**

Light

Light is electromagnetic radiation ($\boldsymbol{E}$, $\boldsymbol{B}$) that can be perceived by the human eye.
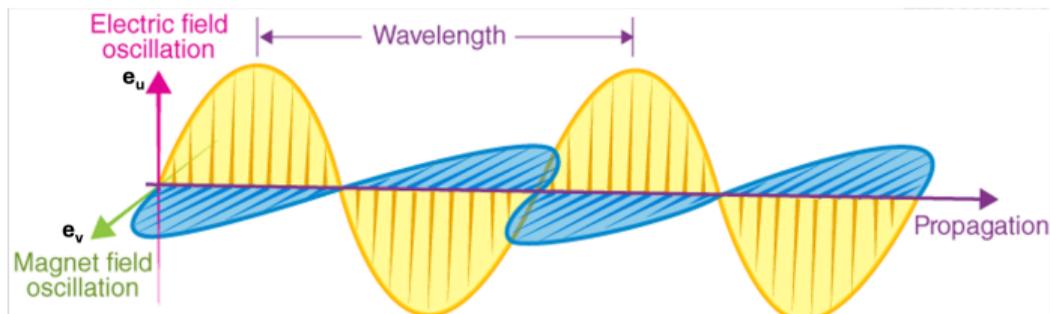


$$\boldsymbol{E}(\boldsymbol{r}, t) = E_0 \cos\left(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t\right) \boldsymbol{e_u}$$

$$\boldsymbol{B}(\boldsymbol{r}, t) = B_0 \cos\left(\omega t - \boldsymbol{k} \cdot \boldsymbol{r}\right) \boldsymbol{e_v}$$

where $\boldsymbol{k} = \frac{\omega}{c} \perp \boldsymbol{e_{u,v}}$ is the wave vector; $\omega = 2\pi f$ is the pulsation.

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**Non-Destructive Testing (NDT)**                                                                                                          47 / 74

**A few words on the physics behind it II**

### Polarization

It is the orientation of the oscillations of light waves in a specific direction ($e_{u,v}$). Ordinary light vibrates in all directions, like chaotic waves. Plane-polarized light, on the other hand, is like *"combed"* light: its waves only vibrate in one plane. There are several types of polarization, including plane, circular, and elliptical.
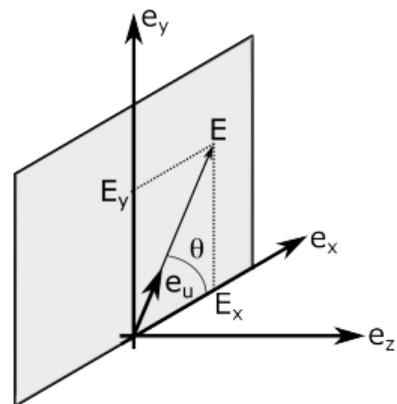
$$\boldsymbol{E} = \begin{pmatrix} E_x \\ E_y \\ 0 \end{pmatrix} = \begin{pmatrix} E_0 \cos\left(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t + \phi_x\right)\cos\theta \\ E_0 \cos\left(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t + \phi_y\right)\sin\theta \\ 0 \end{pmatrix} \Rightarrow \begin{pmatrix} E_0 \cos\left(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t'\right)\cos\theta \\ E_0 \cos\left(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t' + \phi\right)\sin\theta \\ 0 \end{pmatrix}$$

where $\phi = \phi_y - \phi_x$

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**Non-Destructive Testing (NDT)**    48 / 74

**A few words on the physics behind it III**

Linearly polarization

$\Rightarrow \phi = 0$

$$\boldsymbol{E} = E_x \cos\left(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t\right) \boldsymbol{e_x} + E_y \cos\left(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t\right) \boldsymbol{e_y}$$

**A few words on the physics behind it III**

Linearly polarization

$\Rightarrow \phi = 0$
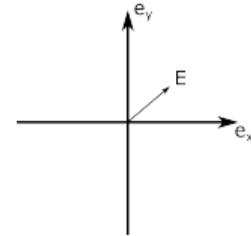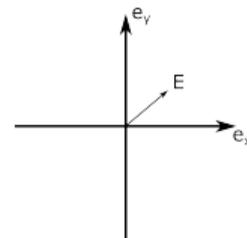
$$\boldsymbol{E} = E_x \cos\left(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t\right) \boldsymbol{e_x} + E_y \cos\left(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t\right) \boldsymbol{e_y}$$

Elliptical polarization

$\Rightarrow \phi = \frac{\pi}{2} + 2\pi p, p \in \mathbb{Z}$ **and** $E_x \neq E_y$

$$\boldsymbol{E} = E_x \cos\left(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t\right) \boldsymbol{e_x} \pm E_y \sin\left(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t\right) \boldsymbol{e_y}$$
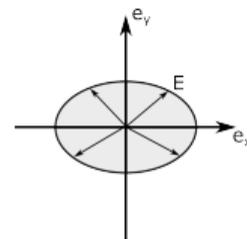
**A few words on the physics behind it IV**

Circular polarization

$\Rightarrow \phi = \frac{\pi}{2} + 2\pi p, p \in \mathbb{Z}$ **and** $E_x = E_y = E_0$
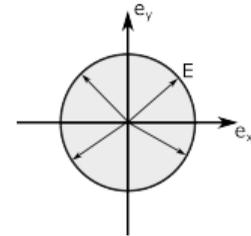
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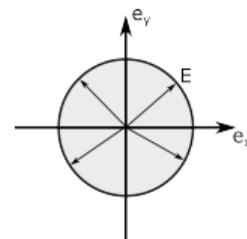
Polarizer

It is an optical filter that passes light of a specific polarization while blocking others, typically made from aligned polymer chains ($\| \boldsymbol{e_p}$). Orthogonally polarized waves do not interfere.
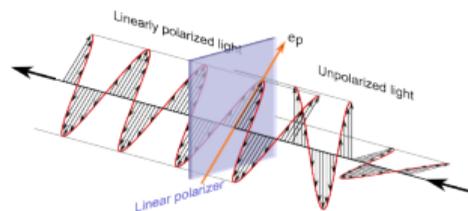
$$\boldsymbol{E'} = \boldsymbol{E} \cos\left(\widehat{\boldsymbol{e_y}, \boldsymbol{e_p}}\right) \boldsymbol{e_p} \Rightarrow I \propto \boldsymbol{E'}^2$$

**A few words on the physics behind it V**

### Light refraction

When light enters a new material, it bends due to a
change in refractive index, as described by the law
of Snell and Descartes:

$$n_1 \sin i_1 = n_2 \sin i_2$$

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Non-Destructive Testing (NDT)                                                                                                                                           51 / 74
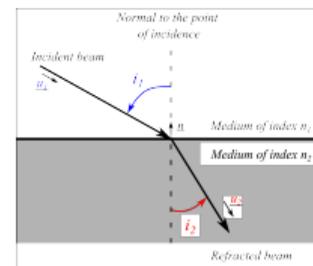
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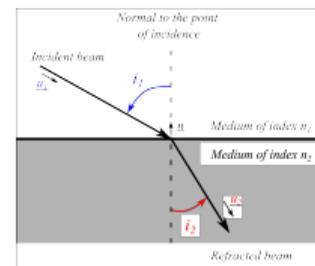


## Natural birefringence



In anisotropic media, for a given propagation direction, there are two polarization directions that remain unchanged during propagation. These two directions are perpendicular to each other and have different refractive indices ($n_2 \neq n_2'$).

**A few words on the physics behind it V**

### Accidental birefringence

Some transparent materials become anisotropic under stress, with the refractive index depending on the principal stress directions. The maximal and minimal refractive indices align with the principal stresses and are proportional to their intensity. By definition:

$$n_2 = \frac{c}{v_2} \neq \frac{c}{v_2'} = n_2'$$

$\Rightarrow$ One wave will be delayed with respect to the other.

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$$n_2 = \frac{c}{v_2} \neq \frac{c}{v_2'} = n_2'$$

$\Rightarrow$ One wave will be delayed with respect to the other.
$\Rightarrow$ There is a phase difference between the two waves, defined as:

$$\phi = \frac{2\pi C d}{\lambda} (\sigma_1 - \sigma_2)$$

where $d$ the thickness and $C$ the photoelasticity constant.

## Visualization of the photoelasticity information [9]
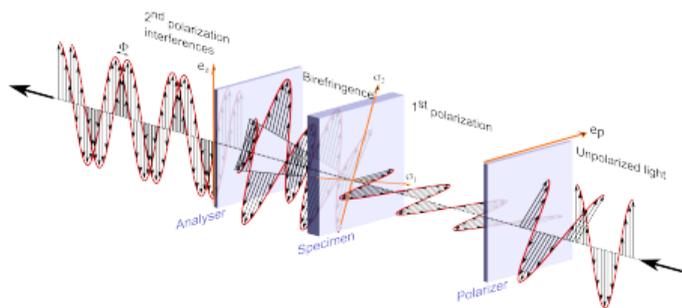


The specimen is placed between two polarizers oriented such that $\widehat{e_p, e_a} = 90°$. Therefore $I = I_0 \cos^2 (\widehat{e_p, e_a}) = 0$ (Malus's law).

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- Unpolarized light passes through the first polarizer, becoming polarized along $\boldsymbol{e_p}$.

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**Non-Destructive Testing (NDT)**                                                                                                    53 / 74

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Non-Destructive Testing (NDT)     53 / 74

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- Unpolarized light passes through the first polarizer, becoming polarized along $\boldsymbol{e_p}$.

- This $\boldsymbol{e_p}$-polarized light passes through the stressed specimen, creating two waves parallel to the principal stress directions, with one wave delayed by $\phi$.

- After passing through the second polarizer (the analyzer), only the components along $\boldsymbol{e_a}$ remain, causing the two waves to interfere. This interference results in a light intensity pattern dependent on $\phi$.

**1** General information

**2** Background on NDT

**3** Some examples of common NDT

**4** Some examples of less-common NDT
   Photoelasticity
   **Radiography**
   Tomography
   Thermography
   Eddy-current testing

**Principle of the radiography**

### Basic principle

It uses X-rays or $\gamma$ rays to inspect an object's internal structure non-destructively. The radiation creates an image on a detector based on how it is absorbed by different materials, revealing internal defects like cracks or voids for expert analysis.

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### Pros/Cons

- **Pros:** internal inspection, permanent record, versatile, detailed analysis…
- **Cons:** radiation risks, specialized equipment, skilled interpretation…

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**Non-Destructive Testing (NDT)**     55 / 74

## A few words on the physics behind it I

### Ionizing radiation

It consists of subatomic particles or electromagnetic waves with enough energy ($E_{rad} \approx 10\,\text{keV}$) to remove electrons from atoms or molecules, thereby ionizing them ($E_{ion} \approx 10\,\text{eV}$)
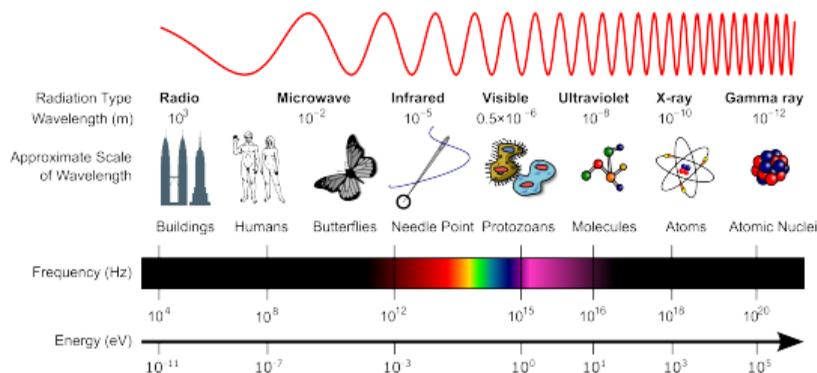


$$E = h\nu = \hbar\omega$$

where $h$: Planck's constant; $\nu$: frequency; $\omega$: pulsation

$$1\,\text{eV} \approx 1.60 \times 10^{-19}\,\text{J}$$

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**Non-Destructive Testing (NDT)**     56 / 74

**A few words on the physics behind it II**

Photon-matter interaction [10]

The main processes of photon-matter interactions are:

- Photoelectric effect
- Compton scattering
- Pair production
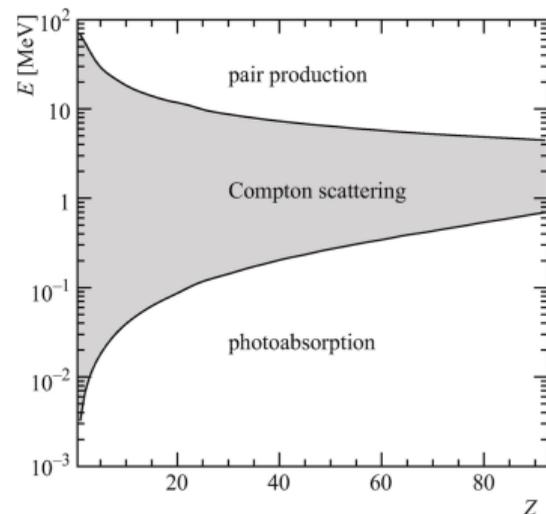
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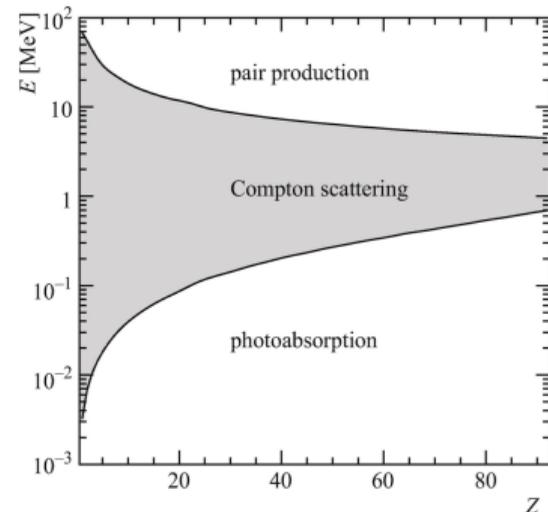


Cross section

It is a measure of the probability that a specific process will occur during a collision between two particles. (Unit: $1\,\mathrm{b} = 1 \times 10^{-28}\,\mathrm{m}^2$)

**A few words on the physics behind it III**

### Photoelectric effect

A photon transfers all its energy to an electron, ejecting it if the energy exceeds the electron's binding energy.



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**Non-Destructive Testing (NDT)**      58 / 74

**A few words on the physics behind it III**

### Photoelectric effect

A photon transfers all its energy to an electron, ejecting it if the energy exceeds the electron's binding energy.

$\lambda$

$e^-$

### Compton scattering

$\lambda'$

$\theta$

$\lambda$

$e^-$
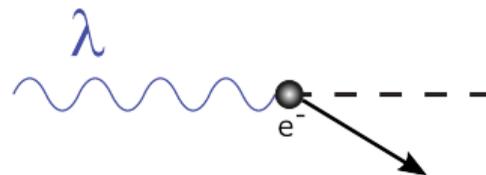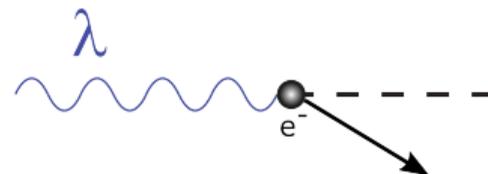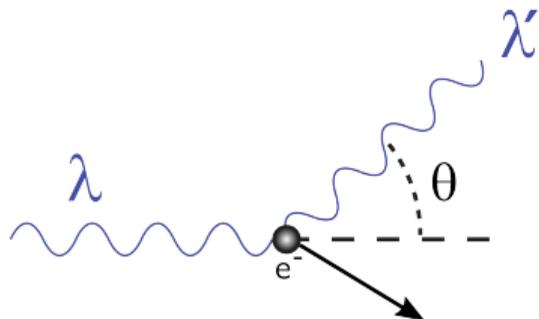
An incident photon collides with a free or loosely bound electron, losing energy and changing direction. The electron gains this energy and is ejected with a new direction and velocity.

**A few words on the physics behind it IV**

Pair production

A high-energy photon interacts with an atom's
nucleus and converts into an electron-positron pair.
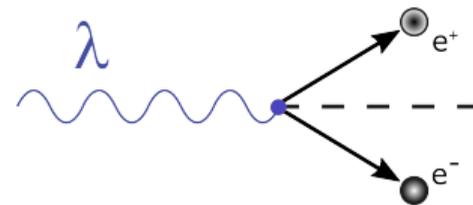
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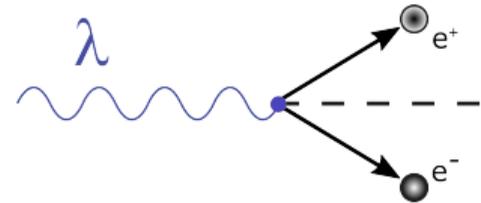


### Other processes

- **Rayleigh Scattering:** It occurs when photons interact with particles smaller than their wavelength, scattering without a change in wavelength.
- **Fluorescence**
- **Raman effect**
- **Auger effect**
- …

**A few words on the physics behind it V**

Attenuation laws

When a photon beam hits a material at normal incidence, some will interact, defining an interaction probability $\mu$ per unit length:

$$\mu = \mu_{Photoelectric} + \mu_{Compton} + \mu_{Pair}$$

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**Non-Destructive Testing (NDT)**                                                                                                              60 / 74

**A few words on the physics behind it V**

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$$\bar{\ell} = \frac{1}{\mu}$$

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And the average distance traveled by a photon before interacting, known as the mean free path:

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The number $N$ of photons transmitted through the specimen with density $\rho$ and thickness $t$ is given by the Beer-Lambert law ($N_0$ being the initial number of photons):

$$N = N_0 \exp\left(-\mu t\right) = N_0 \exp\left(\mu_\rho \times \rho t\right)$$

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**Non-Destructive Testing (NDT)**     60 / 74

**1** General information

**2** Background on NDT

**3** Some examples of common NDT

**4** Some examples of less-common NDT
  Photoelasticity
  Radiography
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  Thermography
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**Principle of the tomography**

### Basic principle

It creates detailed 3D images of the internal
structure of objects. It works by taking multiple
X-ray images of an object from different angles.
These images are then processed using computer
algorithms to reconstruct a cross-sectional, 3D
image of the object's interior.

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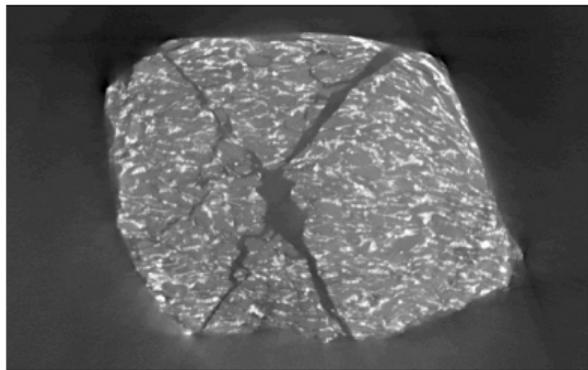


### Pros/Cons

- **Pros:** high resolutions, versatile, 3D visualization...
- **Cons:** radiation risks, cost, artifact and noise, complex interpretation...

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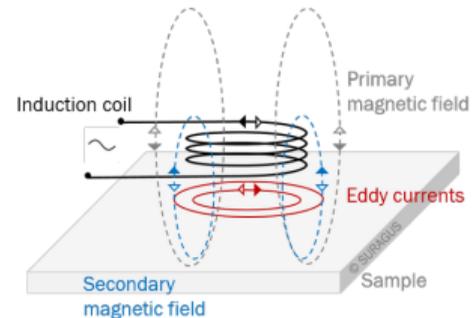**Non-Destructive Testing (NDT)**     62 / 74

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**Principle of the thermography**

## Basic principle

It uses infrared cameras to detect heat emitted by objects, capturing infrared radiation and converting it into an image where different colors represent different temperatures, revealing heat patterns and anomalies.

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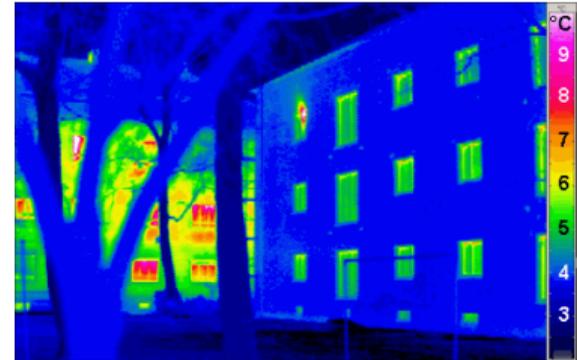


### Pros/Cons

- **Pros:** real-time analysis, broad applications...
- **Cons:** limited depth penetration, cost, environmental sensitivity, requires
  expertise...

## A few words on the physics behind it I [11]

### Black-body radiation

All ordinary matter emits electromagnetic radiation when its temperature is above absolute zero. This radiation can be approximated as blackbody radiation, which is emitted by a body in thermodynamic equilibrium, with a spectrum and intensity that depend solely on the body's temperature.

**A few words on the physics behind it II [11]**

Planck's law

The spectral radiance $L$ is given as:

$$L(\nu, T) = \frac{2h\nu^3}{c^3} \frac{1}{\exp\left(\frac{h\nu}{k_B T}\right) - 1}$$

## A few words on the physics behind it II [11]

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### Wien's displacement law

The wavelength $\lambda_m$ that maximizes the radiance is given as:

$$\lambda_m = \frac{2.898 \times 10^{-3} \, \mathrm{m\,K}}{T}$$
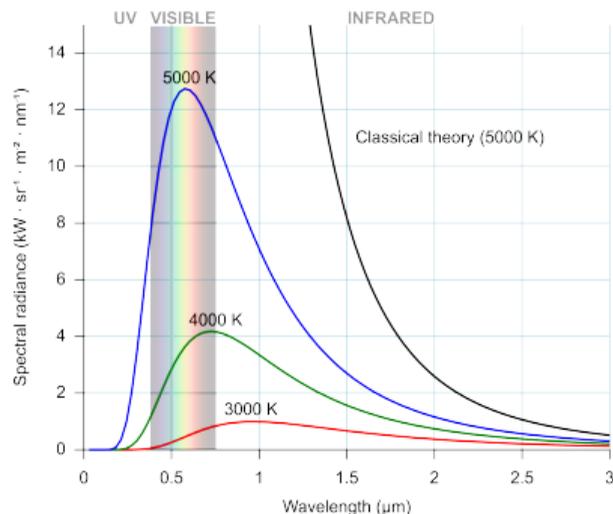


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Non-Destructive Testing (NDT)                                                                                      66 / 74

## Principle of the eddy-current testing

### Basic principle

It works by generating an alternating current in a coil, which creates a changing magnetic field. This magnetic field induces circulating currents, known as eddy currents (or Foucault currents), in the material being tested. Flaws like cracks or corrosion disrupt these eddy currents, altering the magnetic field and coil impedance

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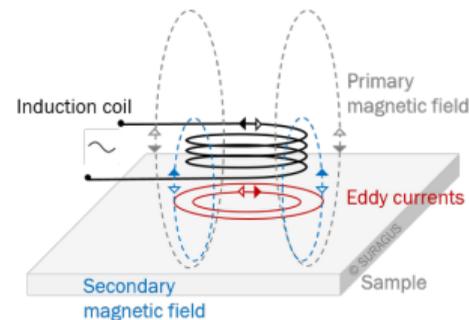


### Pros/Cons

- **Pros:** high sensitivity, no need for contact, versatile, instant results...
- **Cons:** limited to conductive materials, surface sensitive, skill required ...

## A few words on the physics behind it I [12]

### Faraday's law of induction

A time-varying magnetic field $\boldsymbol{B}$ induces an electromotive force (*emf*) in a conductive medium:

$$emf = -\frac{\mathrm{d}\Phi_B(t)}{\mathrm{d}t} \quad \text{where} \quad \Phi_B(t) = \iint_S \boldsymbol{B}(t)\boldsymbol{n}\mathrm{d}S$$

This occurs because the electric charges are subjected to the Lorentz force when they move through $\boldsymbol{B}(t)$.

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**Non-Destructive Testing (NDT)**                                                                                              69 / 74
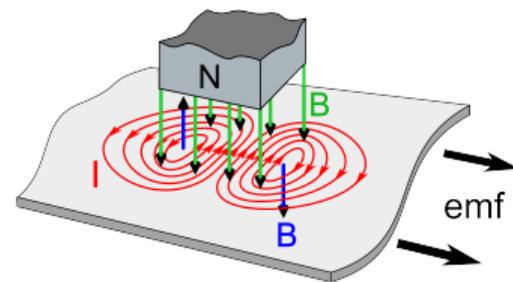
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This occurs because the electric charges are subjected to the Lorentz force when they move through $\boldsymbol{B}(t)$.



Lenz's law

It states that induced currents always create a magnetic field that opposes the change in the original magnetic field. If the magnetic field increases, the induced field opposes it. If the magnetic field decreases, the induced field supports it.
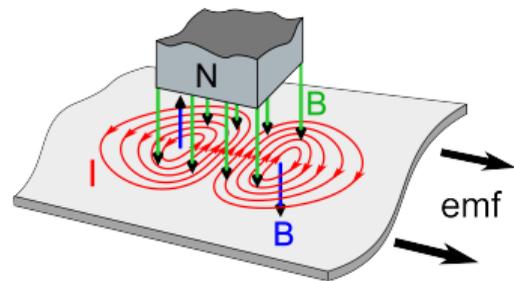
**A few words on the physics behind it II [12]**

Impedance

The impedance ($\underline{Z}$) is the opposition to alternating current in a circuit, resulting from the combined effects of resistance ($R$) and reactance ($X$):

$$\underline{V} = \underline{Z}I \quad \underline{Z} = R + jX; \quad \underline{Z} \in \mathbb{C}$$

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### Reactance

The reactance of the coil alone is: $X_C = L\omega = L2\pi f$ where $L$ is the inductance of the coil in H. The reactance of the coil close to the conductor is:
$X = X_C + X_{eddy} = l\omega + X_{eddy}$.
Defects alter the observed reactance by affecting the distribution of the magnetic flux and eddy currents within the material.

General information
Background on NDT
Some examples of common NDT
Some examples of less-common NDT
References

*That's all Folks!*

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**Non-Destructive Testing (NDT)**            72 / 74

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