Department of
Mechanical Engineering

# Introduction to Non-Destructive Testing (NDT)

**Professor Pedro Vilaça ***
Advanced Manufacturing and Materials (AM2)

* Contacts
Address: P.O. Box 14200, FI-00076 Aalto, Finland
Visiting address: Puumiehenkuja 3, Espoo
+358 50 3652110 ; pedro.vilaca@aalto.fi

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- Historical and industrial scope of NDT
- Origin, characterization and classification of defects
- ~~Examples of defects and defective components~~
- Introduction to NDT techniques
- Reliability Assessment of NDT results
- ~~Challenges and future developments~~



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# NDT Techniques
## Introduction

## Non-Destructive Testing (NDT)

*Non-Destructive Examination (NDE), Non-Destructive Inspection (NDI), and Non-Destructive Evaluation (NDE)*

**Definition** by the American Society *for Nondestructive Testing* (ASNDT):

*"…the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system."*

*"…In other words, when the inspection or test is completed the part can still be used."*

**NDT** + Condition Monitoring ⇔ **Safety** of modern societies



# NDT Techniques
## Introduction

The NDT is key in Unified Life-Cycle Engineering concepts, producing a notable amount of information to be shared, with a high level of interactivity, among ALL the teams involved in:

- Total Quality Management system
- Product and Structural Design
- Conventional and Modern Manufacturing
- and Maintenance… i.e. FULL LIFE-CYCLE

**NDT data will drive** the modern societies enabling increasing reliability and cost-effectiveness of the global digitalized world

# NDT Techniques
## Introduction

**What are the main industrial application of NDT?**

1) **Inspection of the base material (raw material) <u>before</u> being processed;**
   (Detection of defects inherent to the material)
2) **Inspection of the products <u>during</u> their manufacture;**
   (Statistical quality control process )
3) **Inspection of the products <u>after</u> manufacture;**
   (Quality control of the final product - detection of defects arising from the manufacture)
4) **Component inspection <u>service</u>;**
   (Equipment maintenance – detection of the source of defect in service )
5) **Characterization of properties of materials and metrology;**
   (Measurement of electrical conductivity, speed of sound, paint and coating thickness, structural variations and characterization of microstructures)
6) **Other emerging / non-industrial applications**
   (e.g.: in preventing and combating terrorist acts)





# NDT Techniques
## Historical Scope

**When and why NDT introduced?**

**NDT throughout the history:**

**Dawn of civilization:**

- Reverberate clay pots
- Examination of eggs in the flame light
- Marking chalk in the metal surface

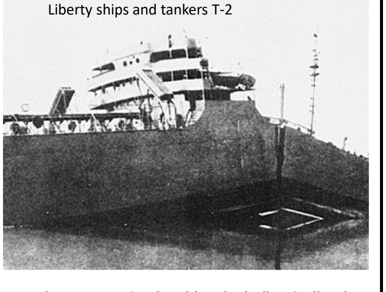
**III century BC:**

- Archimedes uncovers fraud of golden crown of Hiero II, the king of Syracuse
(https://www.math.nyu.edu/~crorres/Archimedes/Crown/CrownIntro.html)

**World War I:** NDT ceaseed to be a “laboratory curosity”

**World War II:** NDT is an essential tool in industries

**Today:** established practise in all industrialized countries




During WWII, 12 USA ships, including 3 Liberties built, broke in half without warning. Suspicion fell on the shipyards which had often used inexperienced workers and new welding techniques to produce large numbers of ships in great haste.
The Ministry of War Transport borrowed the British-built Empire Duke for testing purposes.

# NDT Techniques
## Industrial Relevance

**What are the industrial relevance of NDT?**

**1) Increased Productivity:**
Detection of defect reduces loss of material, labor and production time

**2) Increased Reliability:**
Identifying defects prevent malfunctions, breakdowns and accidents

**3) Cost Reduction**

**In concept, the NDT may be considered as an extension of the 5 human senses**



# NDT Techniques
## Responsabilities

**What are most common causes of failure of components?**

1) Poor Design
(e.g. bad structural design)

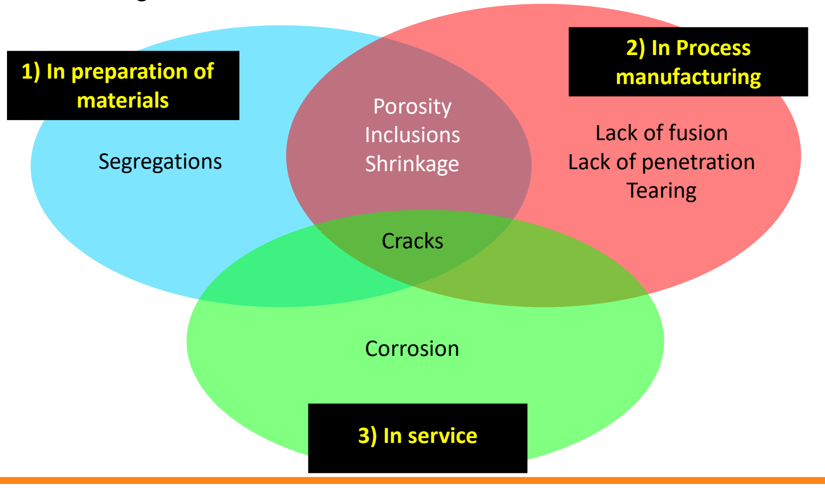
2) Production Error
(e.g. introduction of defects through the used technological processes)

3) Maintenance Error
(e.g. not detecting defects generated in service: corrosion, wear, fatigue)

**Scope of NDT**

# NDT Techniques
## Defects and their Origins

**What is the origin of defects in materials?**






# NDT Techniques
## Defects and their Origins

⇨ **Example:**
**EN ISO 6520 - 1 :2007**

**2 Definitions**

For the purposes of this part of ISO 6520, the following definitions apply.

**2.1**
➡ **imperfection**
any deviation from the ideal weld

**2.2**
➡ **defect**
unacceptable imperfection

# NDT Techniques

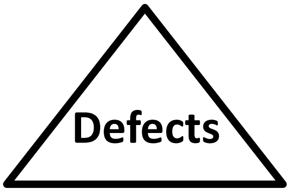
## Defects and their Origins

### Main Defect Features

**Effective application of NDT** requires in-depth knowledge of materials and technological processes
⇒ **Engineering skills**

**Morphology**

Spherical?
Crack?
Delamination?
Physical discontinuity?




Based on these defect features
⇒ Decision to **Accept /Reject** component

**Location**

Superficial?
Subsuperficial?
Internal?

**Dimension**

10 cm?
2 mm?
50 µm?





# NDT Techniques

## Main variants of NDT

**Possible classification of NDT based on their physical principle:**

Electromagnetic radiation
- X ray
- Gamma ray
- Microwaves
- Thermography
- Infrared flash thermography
- Holographic interferometry

Others (absorption, capillarity, vibrations)
- Visual Inspection
- Liquid penetrant (die penetrant)
- Reverberation

Electromagnetism
- Magnetic particles
- Eddy currents
- Eddy currents arrays

Ultrasonic
- Ultrasonic conventional
- Laser ultrasonic
- Termosonics
- ToFD
- Phased arrays
- EMAT
- Guided waves

General procedure in NDT:
1) Application of a test energy to the material (e.g. radiation, ultrasonic, ...)
2) Physical and/or chemical interaction of the energy with the material and imperfections
3) Detection of energy modifications using a suitable detector (probe)
4) Interpretation of obtained information (signals)

## NDT Techniques
Identification (1/2)

- ✓ Visual Testing (VT)
- ✓ Liquid/Die Penetrant Testing (PT)
- ✓ Magnetic Particle Testing (MT)
- ✓ Radiographic Testing (RT)
- ✓ Electromagnetic Testing (ET)
- ✓ Ultrasonic Testing (UT)





## NDT Techniques
Identification (2/2)

- ✓ Acoustic Emission Testing (AE)
- ✓ Guided Wave Testing (GW)
- ✓ Laser Testing Methods (LM)
- ✓ Leak Testing (LT)
- ✓ Magnetic Flux Leakage (MFL)
- ✓ Neutron Radiographic Testing (NR)
- ✓ Thermal/Infrared Testing (IR)
- ✓ Vibration Analysis (VA)

# NDT Techniques
## Visual Testing (VT)

The Visual Testing is based on a simple principle: It consists in clean workpiece and illuminate the piece with a light source and then examine it

The inspection can be carried out by:
- i ) **Direct Observation** (by naked eye);

or auxiliary equipments, such as:
- ii) **Assisted Visual Inspection**;
- iii) **Remote Visual Inspection**:

- Mirrors, magnifying glasses, microscopes and telescopes
  (When you want to increase the size of the discontinuities to observe)

- Profile projectors
  (For example, when it is small-sized pieces)

- Endoscopes
  (When the objective is to inspect the interior walls of a part, e.g. tubes/pipes or tanks)



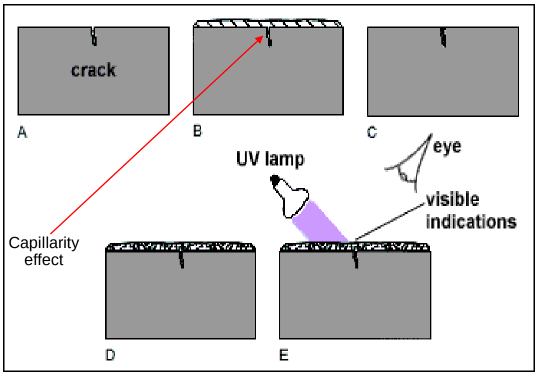
# NDT Techniques
## Visual Testing (VT): Endoscopy

The endoscope is a device consisting of a tube, flexible or rigid, with a built-in optical system which allows to inspect interior surfaces when the tip of the optical system is fed through an orifice which may be smaller than 3 mm

# NDT Techniques

## Liquid/Die Penetrant Testing (PT)

PT is applied to detect defects opened up to the surface of (almost) all materials:
i) with non-porous materials + ii) with low surface roughness




A. Sample before testing
B. Liquid penetrant applied
C. Surplus wiped off leaving penetrant in crack
D. Developer powder applied, dye soaks into powder
E. View colored indications, or UV lamp shows up fluorescent indications.



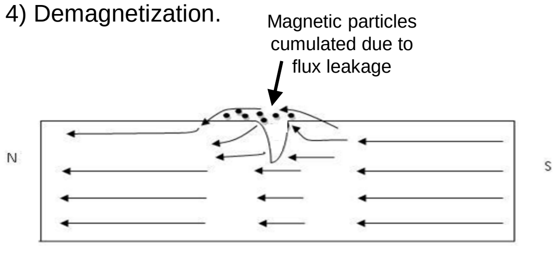


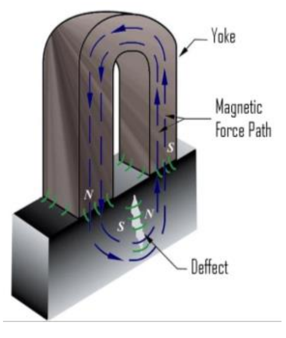
# NDT Techniques

## Magnetic Particle Testing (MT)

MT is used in ferromagnetic materials for the detection of:
i) surface; ii) and near surface flaws

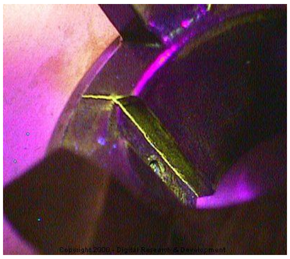
The NDT Magnetic Particle involves main 4 steps:
1) Magnetization of the piece;
2) Application of magnetic particles;
3) Inspection;
4) Demagnetization.



# NDT Techniques

## Magnetic particles



Examples of observation of facts by NDT Magnetic Particle method

**The detection of defects is based on the fact that the magnetic particles are attracted to the <u>drain field areas</u> resulting from defects in the part.**



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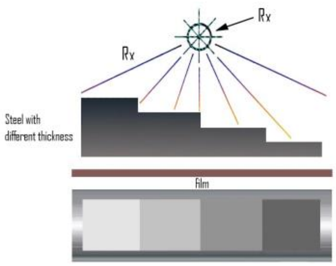
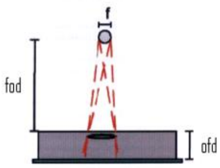
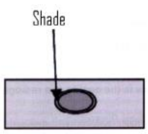
# NDT Techniques

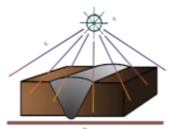
## Radiographic Testing (RT)

A discontinuity in a material, like a void or a change in geometry, and this change causes differences in the degree of radiation absorption




Radiology with root defect



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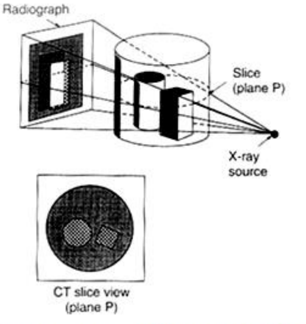
# NDT Techniques
## Computed Tomography (CT) Testing

- CT uses a computer to reconstruct an image of a cross sectional plane of an object as opposed to a conventional radiograph
- CT image is developed from multiple views taken at different viewing angles that are reconstructed using a computer
- computer triangulates using every point in the plane as viewed from many different directions




CT image vs. a radiographic image



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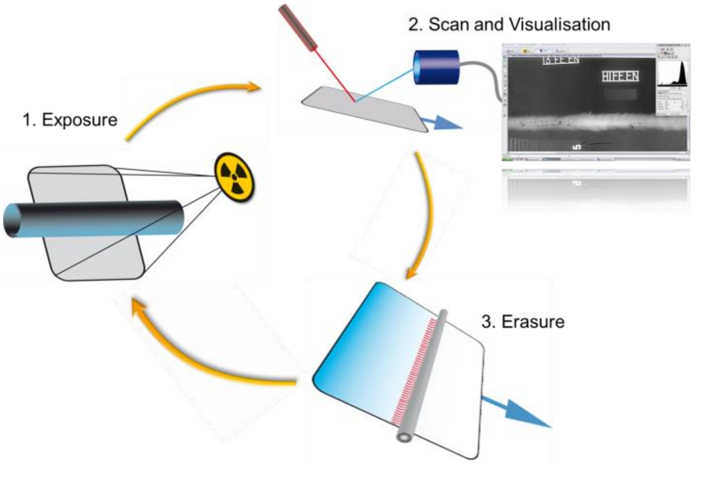
# NDT Techniques
## Digital Radiographic Testing



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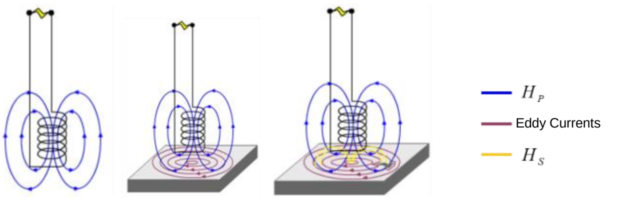
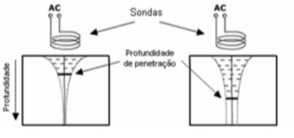
# NDT Techniques
## Electromagnetic Testing (ET)

Eddy current testing, a circular coil carrying an AC current is placed in close proximity to an electrically conductive specimen. The AC current in the coil generates a changing magnetic field, which interacts with the test object and induces eddy currents. Variations in the phase and/or magnitude of these eddy currents can be monitored using a second 'search' coil, or by measuring changes to the current flowing in the primary 'excitation' coil




$$\delta_{(f,\mu,\sigma)} = \frac{1}{\sqrt{\pi f \mu \sigma}}$$



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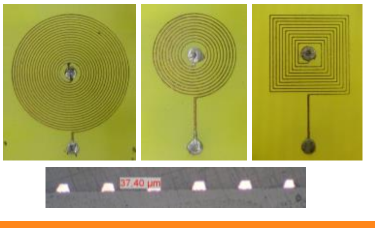
# NDT Techniques
## Electromagnetic Testing (ET)

Ferrite core

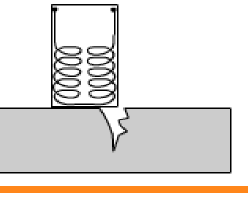
Inner tube

Exterior tubes


Flat spiral coils




Differential design





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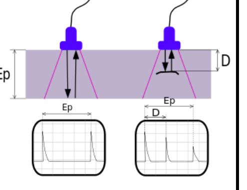
# NDT Techniques
## Ultrasonic Testing (UT)

- UT (f > 20 kHz) inspection involves sending a high frequency, mechanical vibration into material and registering and evaluating any echoes that are detected… Part of the ultra-high frequency sound introduced into the part is reflected back when it hits a material with a different acoustic impedance (density and acoustic velocity)
- UT procedures are widely used for thickness measurement, corrosion monitoring, lamination checks and flaw detection in welds, forgings, castings and pipes
- The most common sound frequencies used in UT are between 1.0 and 10.0 MHz, which are too high to be heard and do not travel through air



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# NDT Techniques
## Ultrasonic Testing (UT)

- Longitudinal Waves

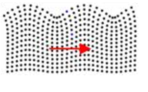
$$C_l = \sqrt{\frac{E}{\rho}\frac{1-\nu}{(1+\nu)(1-2\nu)}}$$

- Transversal Waves



$$C_t = \sqrt{\frac{E}{\rho}\frac{1}{2(1+\nu)}}$$

- Rayleigh Waves



- Lamb Waves

$E$ [N.m$^{-2}$]
$\rho$ [kg.m$^{-3}$]
$\nu$ [m.m$^{-1}$]
$C$ [m.s$^{-1}$]
$\lambda$ [m]
$f$ [s$^{-1}$]

$$C = \lambda \cdot f$$

$$\lambda \leq l_{defect} \leq \lambda$$

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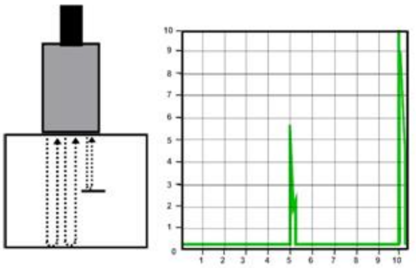
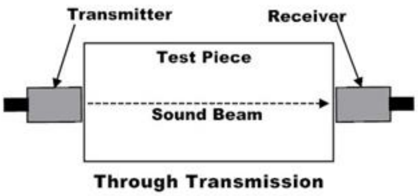
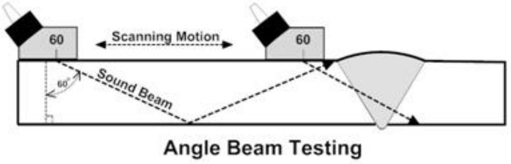
# NDT Techniques
## Ultrasonic Testing (UT)



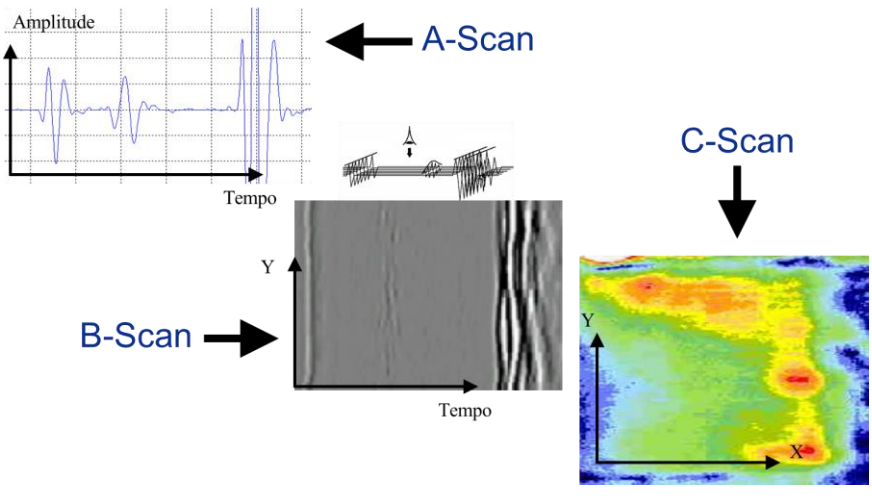




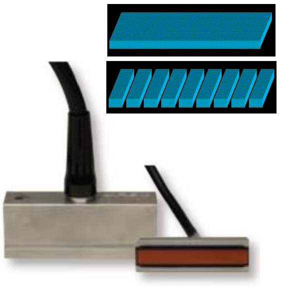


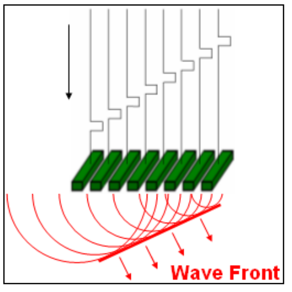

# NDT Techniques
## Ultrasonic Testing (UT)

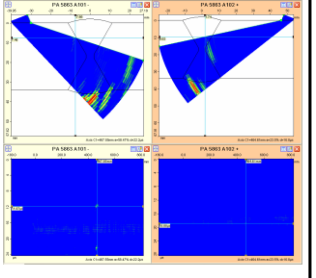


# NDT Techniques
## Ultrasonic Testing (UT): Phased Array (PA)

- PHASED ARRAY (PA) is based on the Huygens principle with a probe integrating numerous elementary transducers. When the elementary transducers are activated accordance with a predefined time law they create a wave with a pre-defined characteristic and focus







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# NDT Techniques
## Reliability Assessment

- ✓ **PoD** (Probability of Detection)
- ✓ **ROC** (Relative Operating Characteristic)



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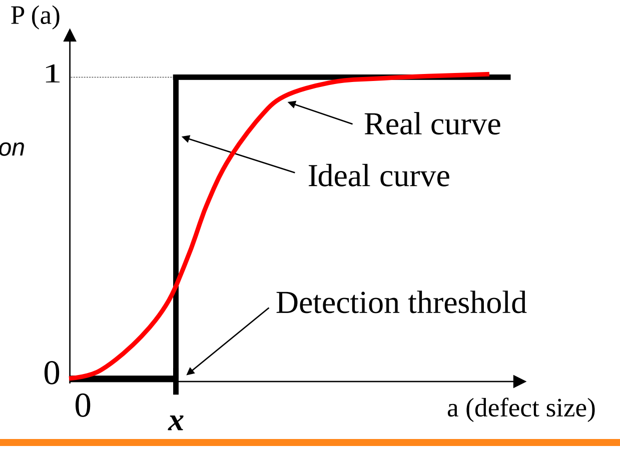
# NDT Techniques
## Reliability Assessment: PoD

**How do you evaluate the confidence level of NDT inspection?**

Criteria 1:
*Probability of Detection* (PoD)

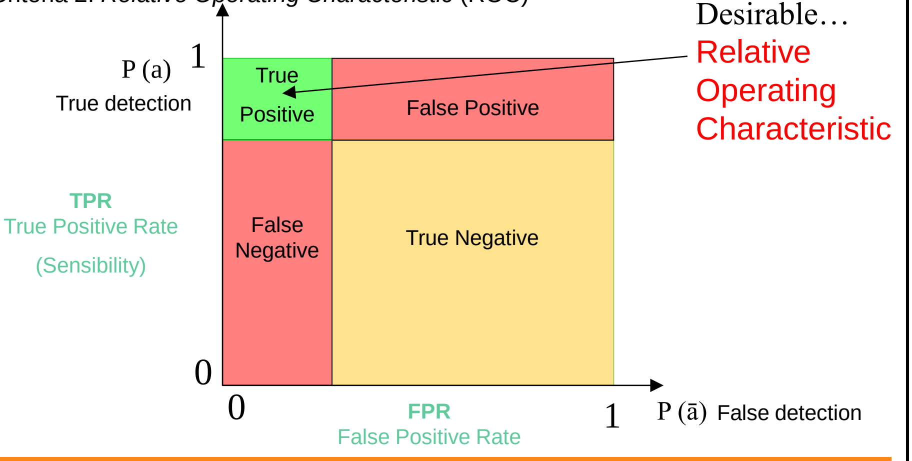






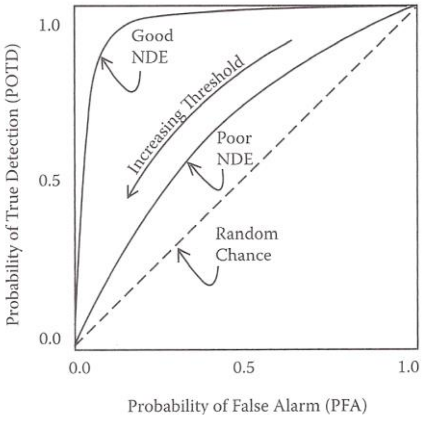

# NDT Techniques
## Reliability Assessment: ROC

Criteria 2: *Relative Operating Characteristic* (ROC)



# NDT Techniques
## Reliability Assessment: ROC

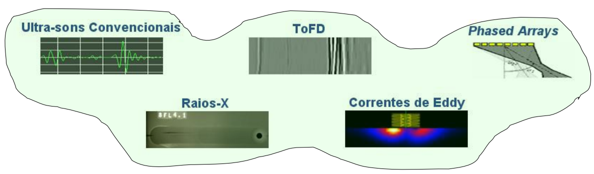
Criteria 2: *Relative Operating Characteristic* (ROC)



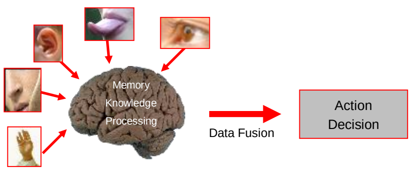





# NDT Techniques
## Future Challenges




Data Fusion




Imprecision
Uncertainity
Incompleteness
Ambiguity
Conflict

⟺

Diversity
Complementarity
Redundancy

Bayesian inference

$$P(A|D_1D_2\cdots D_K E) = \frac{P(A|E)\cdot\prod_{j=1}^{k}P(D_j|AE)}{\sum_{i=1}^{n}\left(P(A_i|E)\cdot\prod_{j=1}^{k}P(D_j|A_iE)\right)}$$

Theory of evidence of Dempster-Shafer

$$m(A)_{fusão} = m_1 \otimes m_2 = \frac{\sum_{A_p\cap A_q=A} m_1(A_p)\cdot m_2(A_q)}{1-\sum_{A_p\cap A_q=\phi} m_1(A_p)\cdot m_2(A_q)}$$