PHYSICAL SENSORS FOR ENVIRONMENTAL SIGNALS

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OUTLINE OF THE COURSE

- Lecture 1: Introduction to environmental signals and physical sensors
- Lab 1: Introduction to instruments for measurements
- Lecture 2: Vibrations: sources and detection
- Lab 2: Characterisation of an acoustic system
- Lecture 3: Distance, position and speed measurement
- Lab 3: Measuring distance with ultrasounds and speed with an accelerometer
- Lecture 4: Electromagnetic radiation: sources and detection
- Lab 4: Detecting and generating light

SENSING THE ENVIRONMENT

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Sources

- Temperature
- Pressure
- Distance and position
- Speed
- Vibrations
- Acoustic
- Radiations: particles & light
- Chemical pollutants

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RADIATION

Radiation is the emission or transmission of energy in the form of waves or particles through space or a material medium.

This includes:

- **electromagnetic radiation** consists of photons, such as radio waves, microwaves, infrared, visible light, ultraviolet, x-rays, and gamma radiation (γ)
- **particle radiation** consists of particles of non-zero rest energy, such as alpha radiation (α), beta radiation (β), proton radiation and neutron radiation

RADIATION

Ionizing and non-ionising radiation

Radiation is often categorised as either *ionising* or *non-ionising* depending on the energy of the radiated particles. Ionising radiation carries more than 10 eV, which is enough to ionize atoms and molecules and break chemical bonds. This is an important distinction due to the large difference in harmfulness to living organisms.

- *Ionising radiation*, such as X-rays, gamma rays and α, β particles, possesses sufficient energy to detach electrons from atoms. It has greater penetrating power, capable of passing through materials deeply. It is utilised in medical imaging (X-rays), cancer therapy, industrial applications (radiography) and particle physics. It has the potential to cause cellular and DNA damage.

- *Non-ionising radiation*, including visible light, radio waves, and microwaves, lacks this energy to ionise matter. The non-ionising radiation, having lower energy, is commonly used in communication (radio waves), heating (microwaves), and illumination (visible light).

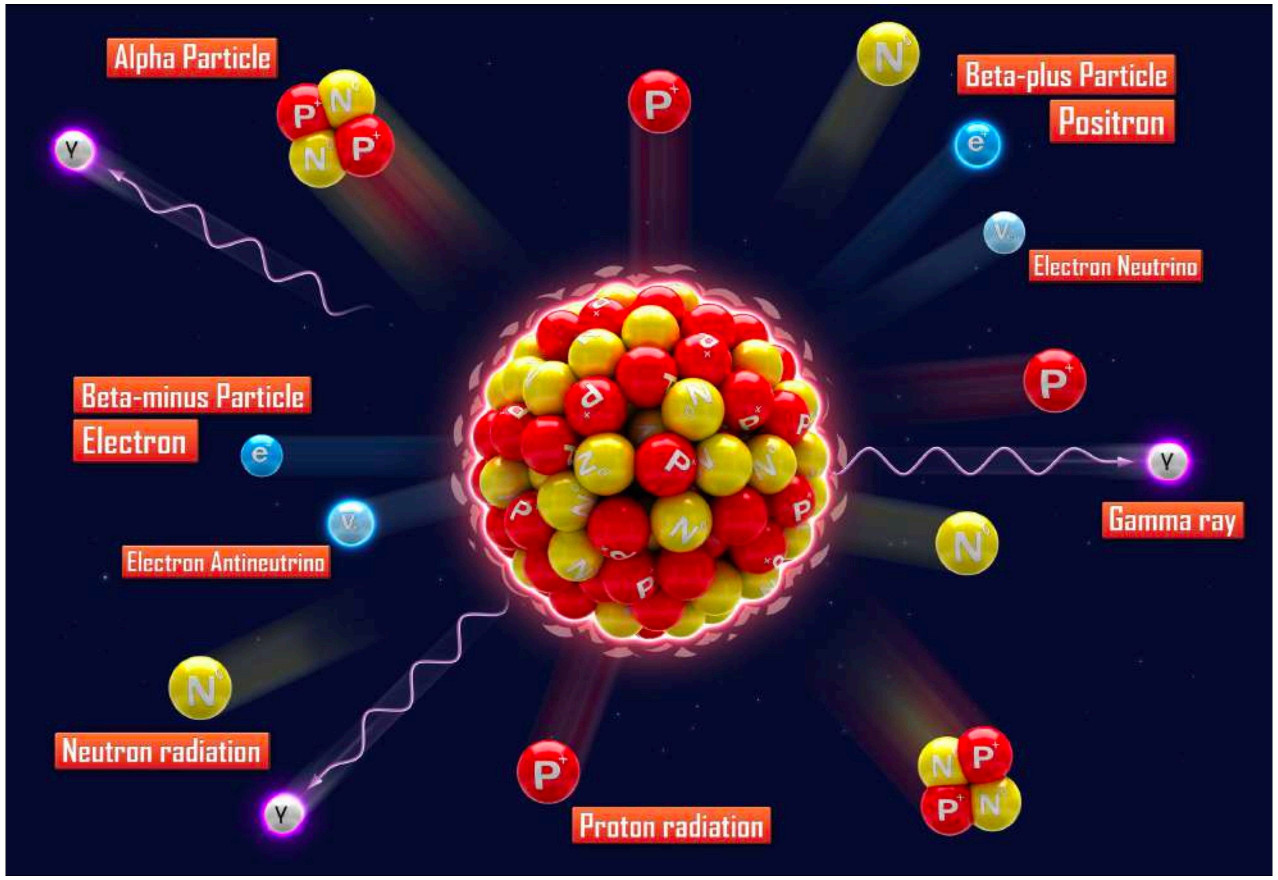
IONISING RADIATION

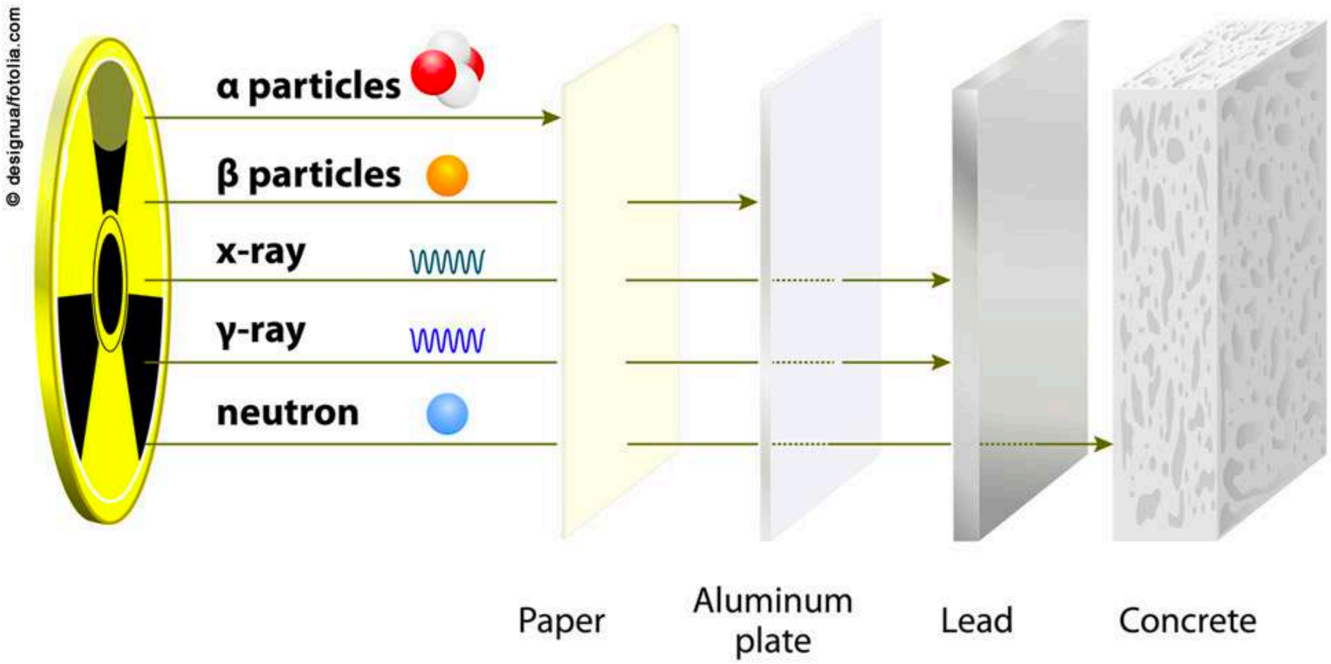
Sources of Ionising Radiation:

Sources of ionising radiation include radioactive materials and radiation-generating machines. Radioactive materials can be naturally occurring (such as uranium and radium found in the Earth) or manmade in an accelerator or reactor.

Types of Ionising Radiation:

Main types of ionising radiation: alpha particles, beta particles, positrons, neutrons, gamma rays, and X-rays





https://www.osha.gov/ionizing-radiation/background

IONISING RADIATION

Type of radiation	Examples
Particle radiation (sub-atomic particles with mass)	
Alpha particles α (^{2+}He)	Radionuclides that emit alpha particles: U-238; Ra-224; Rn-222; Am-241 —> used for smoke detectors; Po-210
Beta particles β- (electrons)	Radionuclides that emit beta particles: - Sr-90 —> nuclear waste product, used for cancer treatment - C-14 —> used for radiocarbon dating
Positrons β+	Radionuclides that emit positrons: - F-18 —> used for PET scanning
Neutrons	Nuclear fission and fusion reactions, as well as neutron sources produce neutrons
Electromagnetic radiation (no mass and no charge)	
Gamma rays γ	Radionuclides that emit gamma rays include: - I-13,Cs-137 —> nuclear waste - Co-60
X-rays	Radionuclides that emit X-rays: I-125, Fe-55 Electronic production of X-rays: X-rays tubes

https://www.iaea.org/newscenter/news/what-is-radiation

IONISING RADIATION: EXAMPLES OF APPLICATION

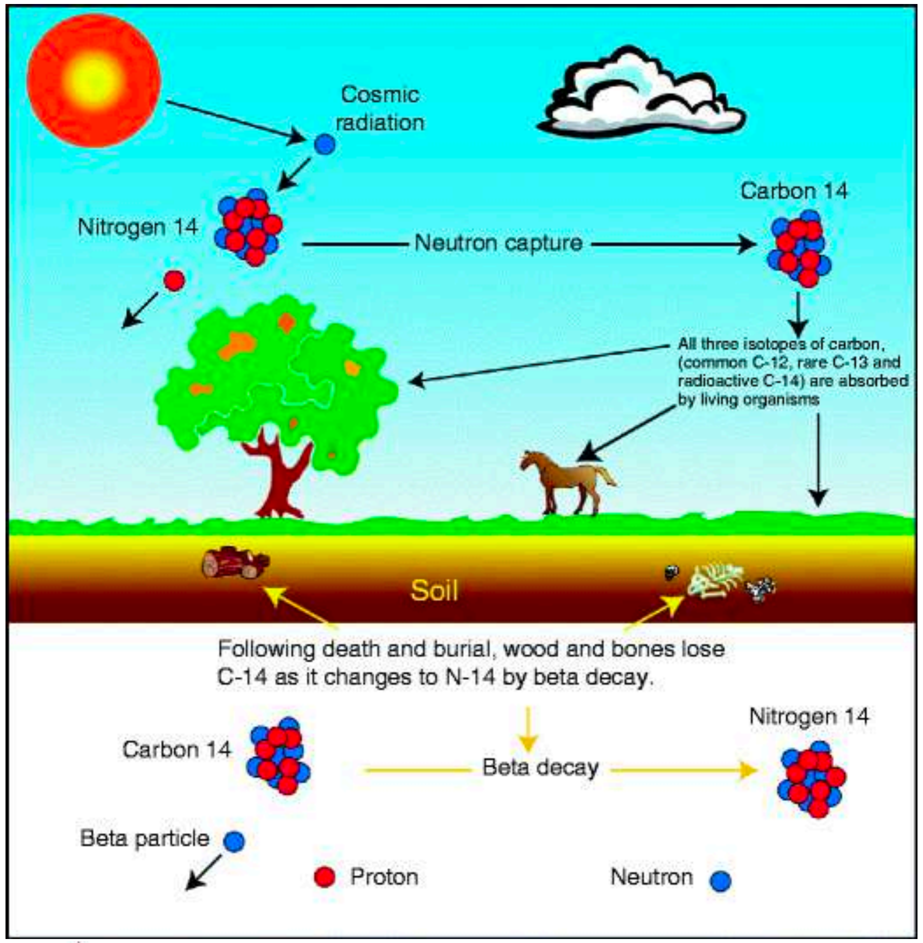
Radiocarbon dating (14C)

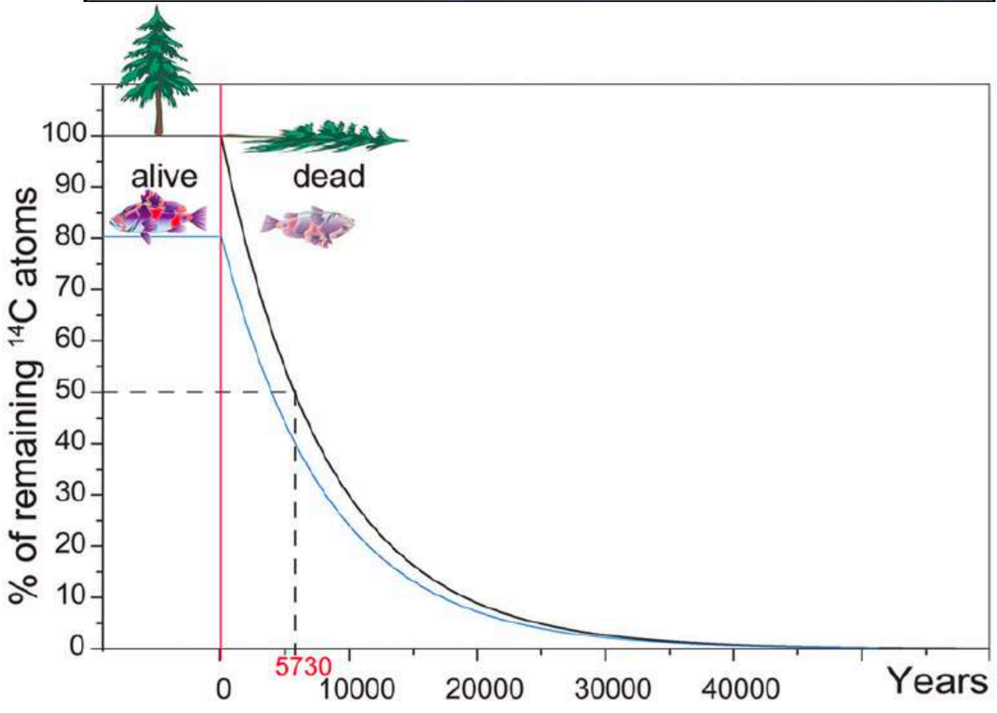
Radiocarbon dating, based on the decay of the radioactive isotope carbon-14 (14C) is a technique used in archaeology, geology, and other scientific fields to estimate the age of organic materials.

14C undergoes radioactive decay over time ($T_{1/2}$ = 5730 yr), converting back to stable 14N.

14C is naturally produced in the atmosphere by cosmic ray activation of 14N. Living organisms continually exchange carbon with their environment, maintaining a balance of 14C in their tissues. However, upon death, this exchange stops, and the 14C begins to decay. By measuring the remaining ratio of 14C to stable 12C in a sample and comparing it to the known decay rate of 14C, it is possible to determine the approximate age of the sample.

The radiocarbon dating provides valuable insights into the timelines of ancient artifacts, archaeological sites, and geological formations within the range of approximately 50,000 years.





https://link.springer.com/referenceworkentry/10.1007/978-90-481-2639-2_127

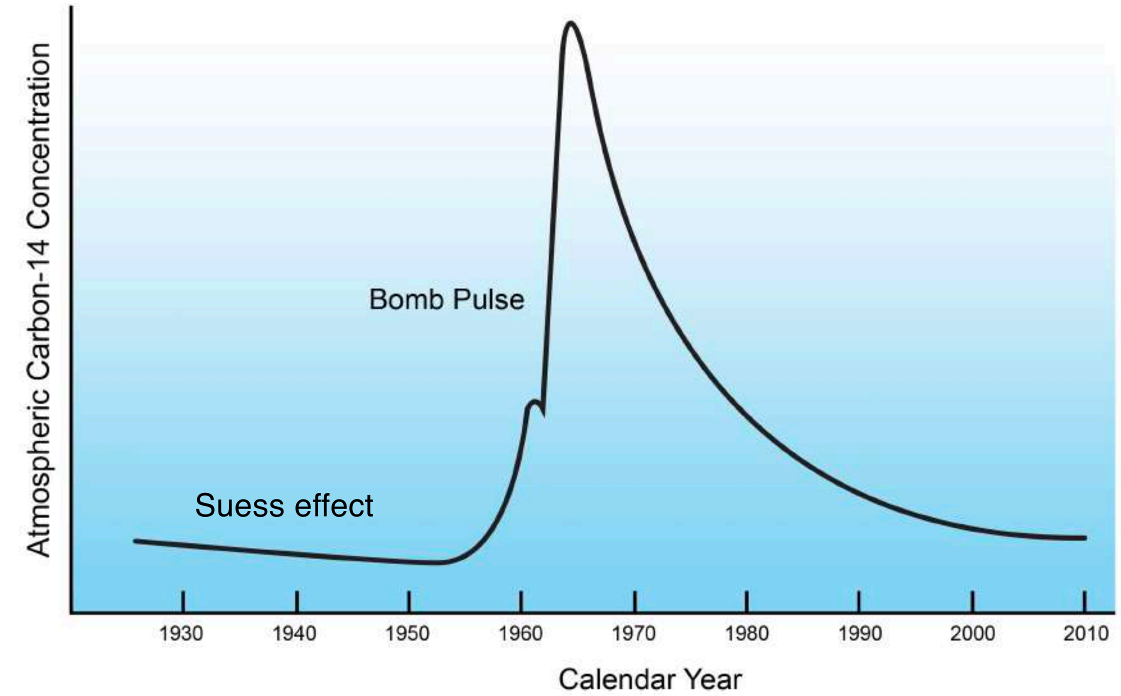
https://news.uchicago.edu/explainer/what-is-carbon-14-dating

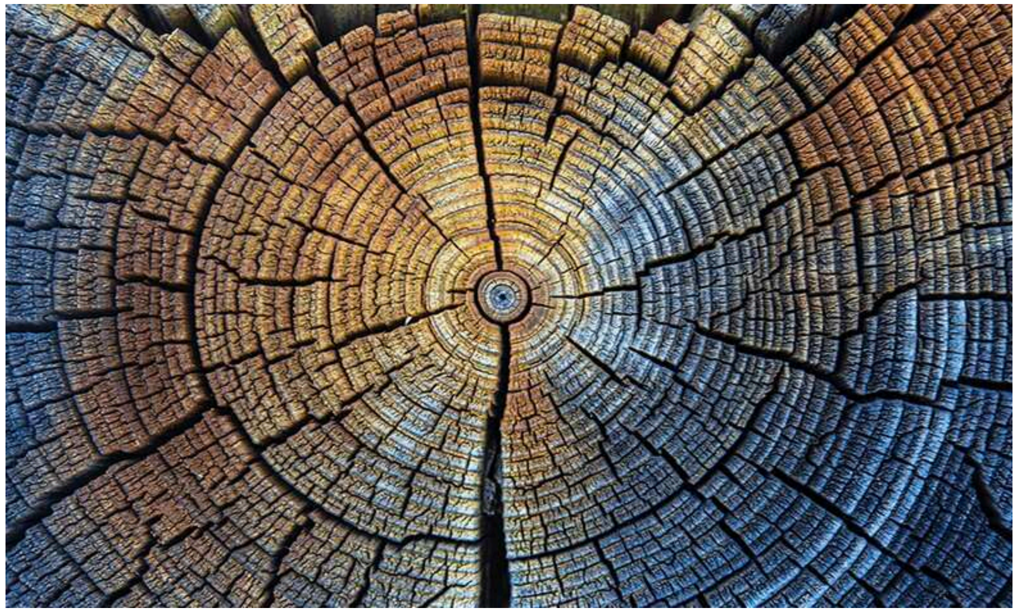
IONISING RADIATION: EXAMPLES OF APPLICATION

Radiocarbon dating (14C) and effect of human activities

There are two human activities recognized to have irreparably changed the global radiocarbon levels—the burning of fossil fuel and nuclear weapons testing.

Burning of large quantities of fossil fuels like coal (Suess effect) had significantly lowered the radiocarbon concentration of the atmospheric carbon reservoir. In contrast, nuclear weapons testing in the 1950s and 1960s dramatically increased the level of 14C in the atmosphere. The phenomenon is often referred to as the bomb effect.





https://www.radiocarbon.com/carbon-dating-bomb-carbon.htm

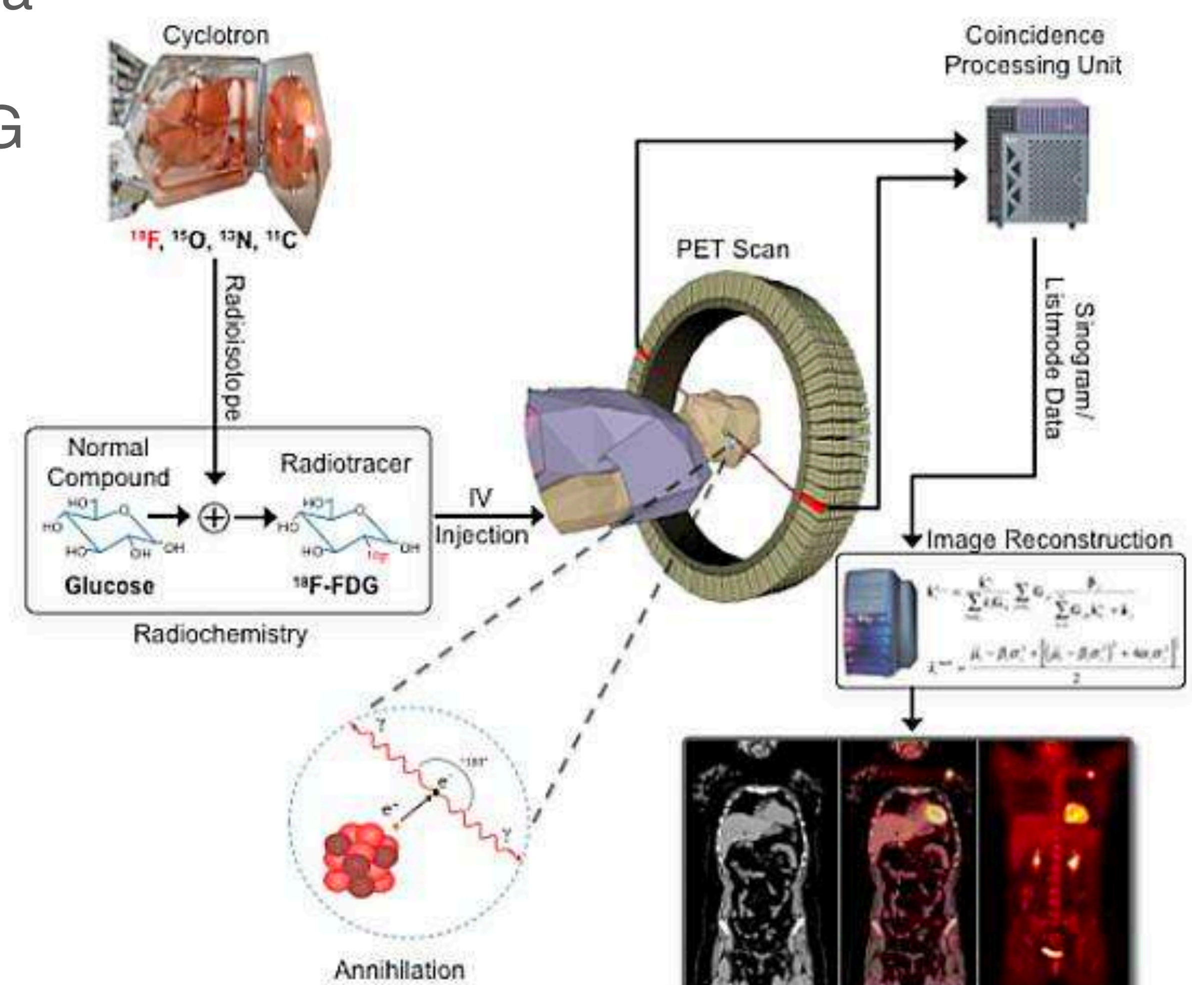
https://phys.org/news/2020-08-secrets-international-carbon-dating-standard.html

IONISING RADIATION: EXAMPLES OF APPLICATION

Positron Emission Tomography (PET)

PET is an advanced medical imaging technique with (low dose) ionising radiation used to visualise metabolic and biochemical processes within the body.

PET scans involve the injection of a small amount of a radioactive tracer substance, commonly a radiolabeled compound like fluorodeoxyglucose (FDG with 18F radionuclide), which is absorbed by tissues and organs depending on their metabolic activity. As the tracer undergoes decay, it emits positrons, which annihilate with electrons in the body, producing gamma rays.



PET scanners detect these gamma rays, creating detailed 3D images that reflect the concentration and distribution of the tracer. By analyzing the pattern of tracer uptake, PET scans provide valuable insights into organ function, tumor growth, brain activity, and other physiological processes, aiding in disease diagnosis, treatment planning, and monitoring therapy response in conditions such as cancer, neurological disorders, and cardiac diseases.

https://www.hopkinsmedicine.org/health/treatment-tests-and-therapies/positron-emission-tomography-pet

NON-IONIZING RADIATION

Types and sources of Non-Ionising Radiation

Non-ionizing radiation is pretty much electromagnetic radiation, including the spectrum of ultraviolet (UV), visible light, infrared (IR), microwave (MW), radio frequency (RF), and extremely low frequency (ELF).

The kinetic energy of the photons of electromagnetic non-ionizing radiation is too small to produce charged ions when passing through matter. The photons have only sufficient energy to change the rotational, vibrational or electronic valence configurations of molecules and atoms.

Type of radiation	Examples
Extremely Low Frequency Radiation (ELF)	Radiation at 60 Hz/50Hz produced by power lines, electrical wiring, and electrical equipment
Radiofrequency (RF) and Microwave (MW) radiation	Sources of RF and MW radiation include radio emitters and cell phones.
Infrared radiation (IR)	Sources of IR radiation include furnaces, heat lamps, and IR lasers
Visible Light radiation	The different visible frequencies of the electromagnetic (EM) spectrum are "seen" by our eyes as different colors.
Ultraviolet radiation	Sources of UV radiation include the sun, black lights, welding arcs, and UV lasers

https://www.osha.gov/non-ionizing-radiation

NON-IONIZING RADIATION: EXAMPLES OF APPLICATION

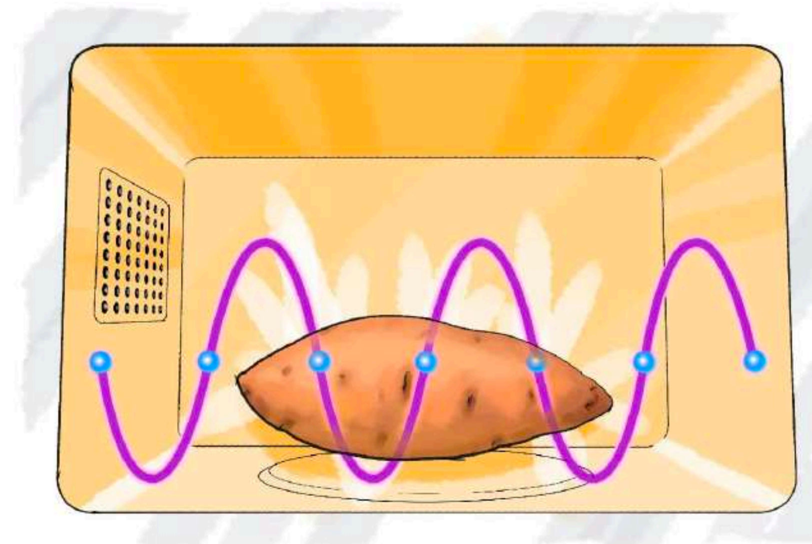
Microwaves for heating food

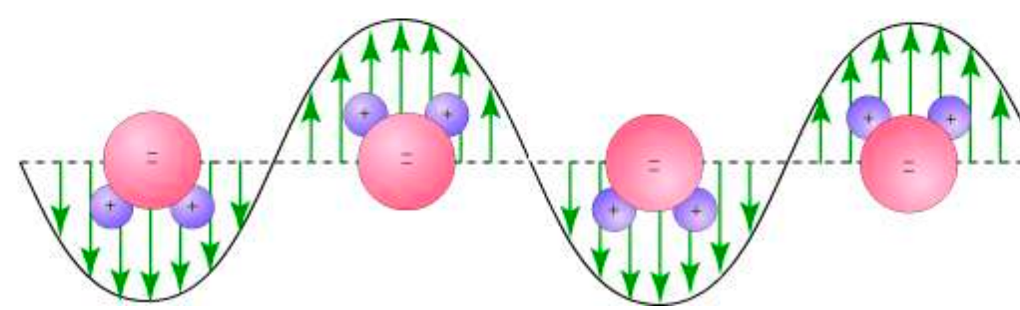
Microwaves work by emitting non-ionizing electromagnetic radiation with a frequency between radio waves and infrared radiation, typically around 2.45 GHz (12.2 cm).

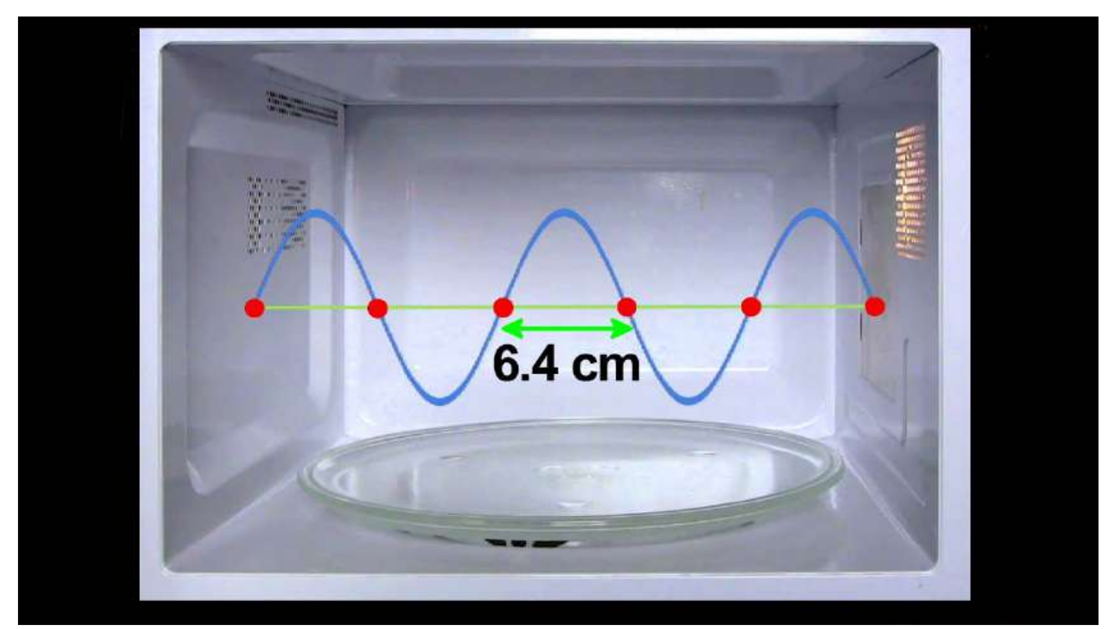
Inside a microwave oven, an electronic device called a magnetron generates these microwaves. The microwaves are then directed into the cooking chamber, where they penetrate food items, having a wavelength comparable with their size.

A microwave oven takes advantage of the electric dipole structure of water molecules, fats, and many other substances in the food, using a process known as *dielectric heating*. These molecules have a partial positive charge at one end and a partial negative charge at the other. In the alternating electric field generated by the microwave, these molecules will constantly spin around, as they continually try to align themselves with the electric field. Therefore these molecules within the food start to vibrate vigorously. The rapid vibration is propagated by collisions to the other non-dipole molecules, sharing the increase in energy deeper into the substance, as molecular rotations, vibrations or other movement. This process indeed generates heat through friction among the molecules, heating the food quickly and evenly. The maximum heating correspond to wave anti-nodes, while zero heating is at the nodes.

In order to distribute the microwaves uniformly, the oven is instrumented with a rotating turntable or stirrer for ensuring consistent heating throughout the food.

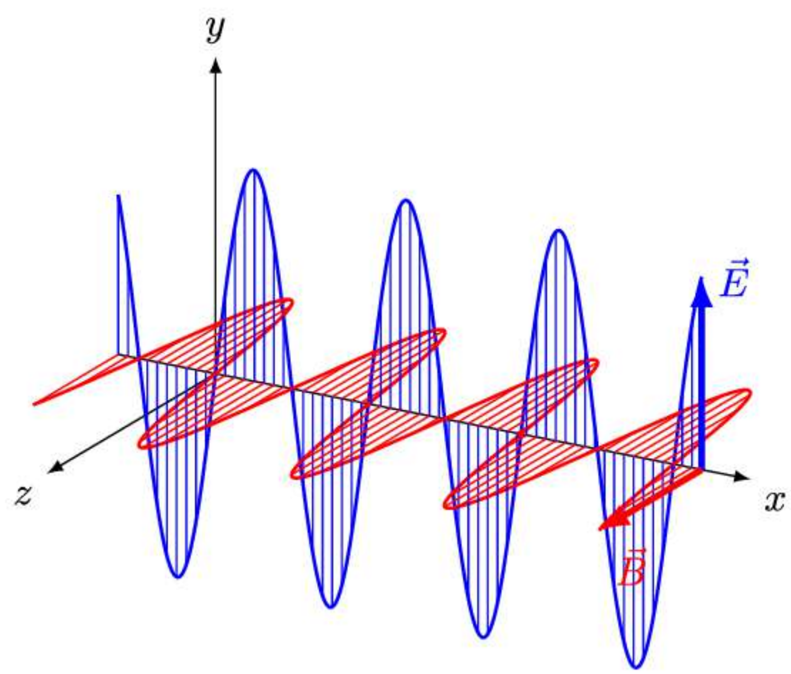




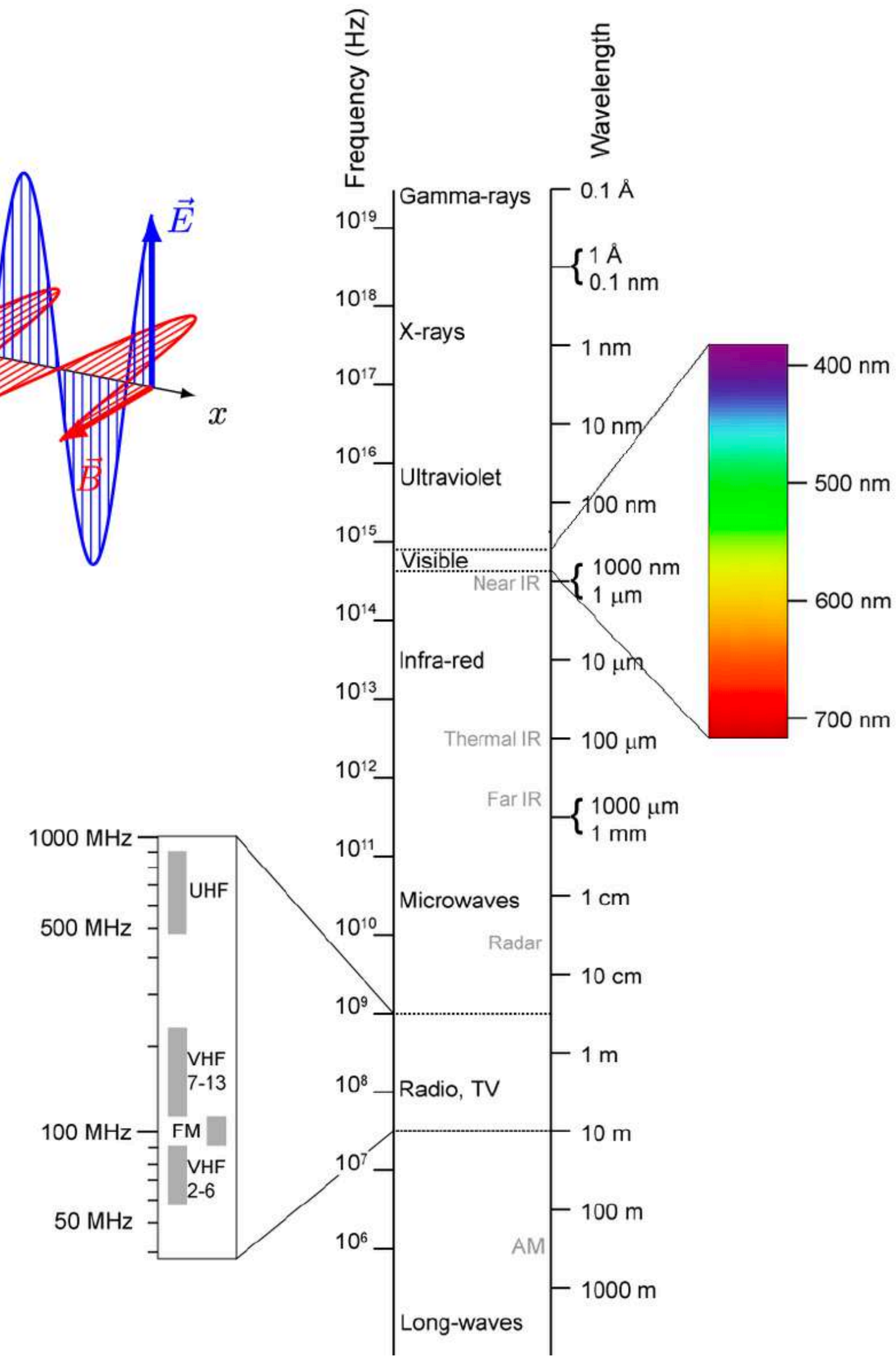


RADIATION: ELECTROMAGNETIC RADIATION

Electromagnetic radiation consists of waves of energy propagated through space, characterised by oscillating electric and magnetic fields at right angles to each other and perpendicular to the direction of wave travel.



The EM radiation spans a wide spectrum of frequencies and wavelengths from radio waves to gamma rays. Each segment of this spectrum represents different forms of electromagnetic radiation, differing in energy levels, frequencies, and interactions with matter.



RADIATION: ELECTROMAGNETIC RADIATION

Electromagnetic radiation exhibits both wave-like and particle-like properties (duality), and its behaviour is governed by Maxwell's equations and quantum mechanics.

$$\nabla E = \frac{\rho}{\varepsilon_0}$$

$$\nabla B = 0$$

$$\nabla \times E = \frac{-\partial B}{\partial t}$$

$$\nabla \times B = \mu_0 \left(J + \varepsilon_0 \frac{\partial E}{\partial t}\right)$$

$$E = h\nu = \frac{hc}{\lambda}$$

E = Energy of a single photon

$h = 6.626 \times 10^{-34}\ \mathrm{J \cdot s}$ (Planck's constant)

ν = frequency (Hz)

λ = wavelength (m)

$c = 2.998 \times 10^{8}\ \mathrm{m/s}$ (speed of light)

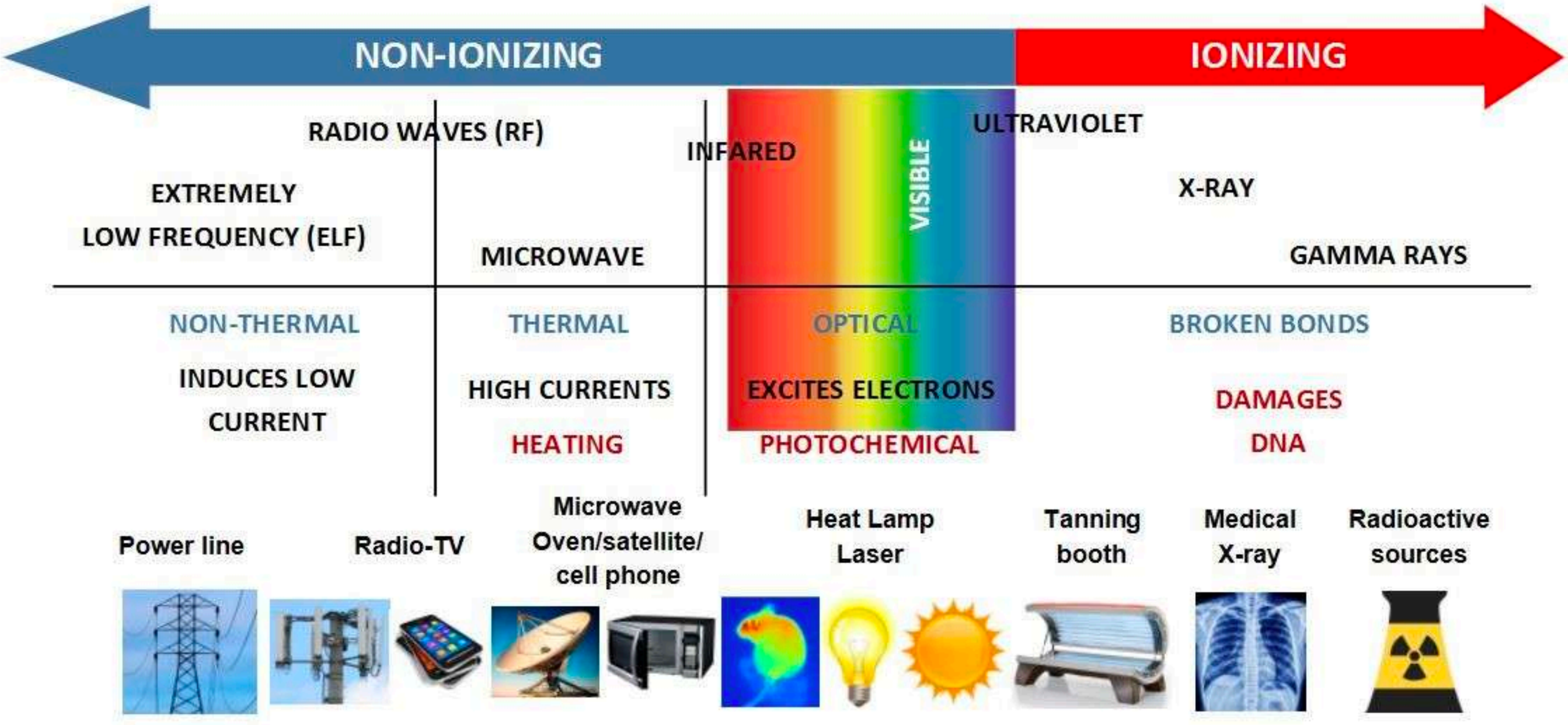
Maxwell's equations:

1. Relation between static electric field and charge density in space
2. No magnetic monopole exists
3. Electric fields can be generated by time-varying magnetic fields
4. Magnetic fields can be generated by time-varying electric fields or by currents

Particle model and quantum theory

- Photons are the electromagnetic quanta

RADIATION: ELECTROMAGNETIC RADIATION



DETECTING RADIATION

Detecting radiation involves identifying and measuring the presence of various types of electromagnetic or particle radiation in an environment or within materials.

Radiation detection relies on specialised instruments designed to detect and quantify these emissions. These instruments respond to radiation by producing measurable signals, such as electrical pulses or light emissions, indicating the presence and intensity of radiation.

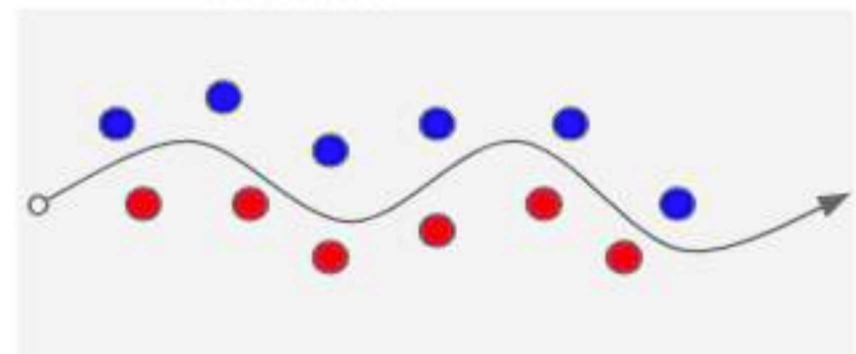
Detection methods vary based on the type of radiation being measured and the specific characteristics of the radiation source, serving critical roles in fields like nuclear medicine, environmental monitoring, radiation safety, and scientific research to ensure accurate measurement and monitoring of radiation levels.

https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull23-4/23405043136.pdf

DETECTING RADIATION

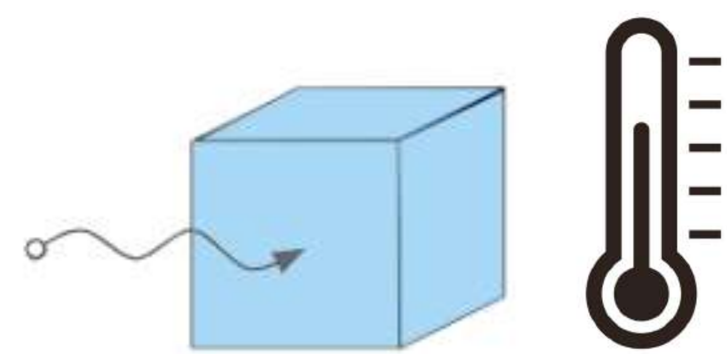
Radiation-matter interaction

1. ****Ionization**** This process occurs when radiation transfers enough energy to atoms or molecules in a material, causing the removal of electrons from their atomic orbits, freeing them. It leads to the formation of pairs of charge carries (e-/ion+, e-/hole).



2. ****Scintillation**** Scintillation is the process where certain materials emit light when exposed to ionizing radiation. When radiation interacts with specific materials like certain crystals or liquid scintillators, it excites their atoms or molecules, causing them to transition to higher energy states. As these excited states return to their lower energy states, they emit photons of light, producing a visible flash or scintillation.

3. ****Heating**** When radiation interacts with matter, it can induce molecular vibrations or rotations in materials, leading to the conversion of radiation energy into thermal energy causing an increase in the material's temperature.



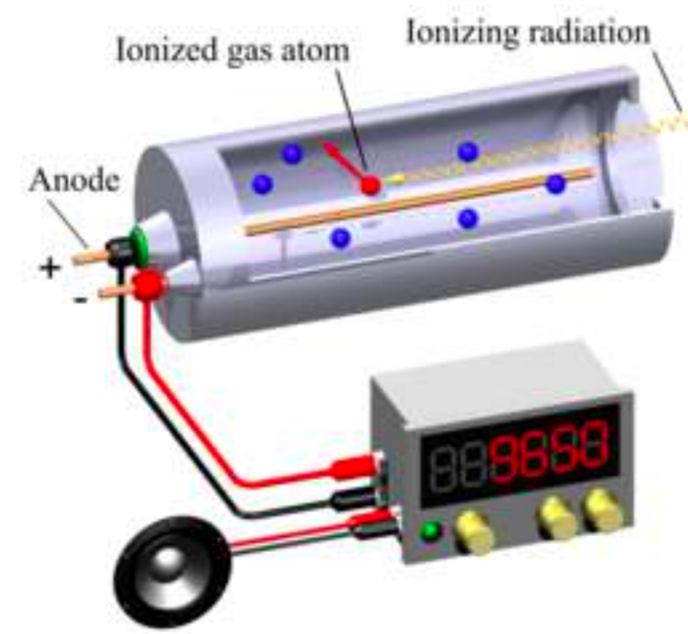
DETECTING IONISING RADIATION IN THE ENVIRONMENT: EXAMPLE

Geiger-Mueller counter

A Geiger-Mueller counter is a radiation detection device based on the ionisation produced in a gas by ionising radiation. The key principle of operation involves detecting the rate of ionisation events caused by incoming radiation within the gas-filled tube.

Geiger counters find applications in radiation monitoring and measurements across various fields, including radiation safety, environmental monitoring, nuclear medicine, and research.

They are particularly useful for detecting and measuring the presence of ionising radiation in the environment, assessing contamination levels, and ensuring radiation safety in various settings. However, it's important to note that Geiger counters have limitations in differentiating between types of radiation and measuring radiation energy levels, as they primarily detect just the presence and intensity (rate/hour, counts/min) of ionising radiation events without distinguishing the specific type or energy of the radiation.

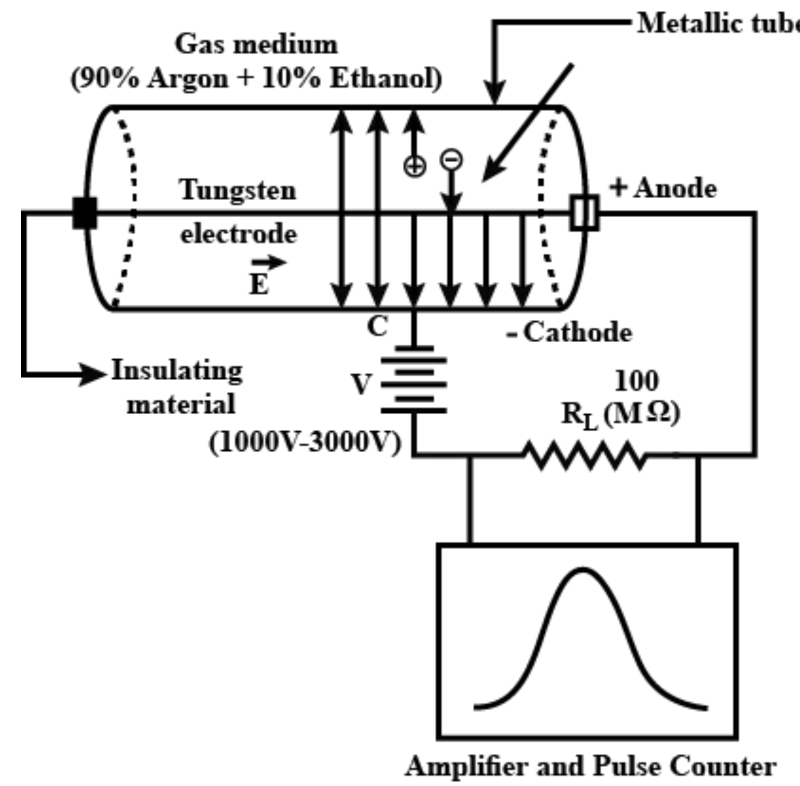


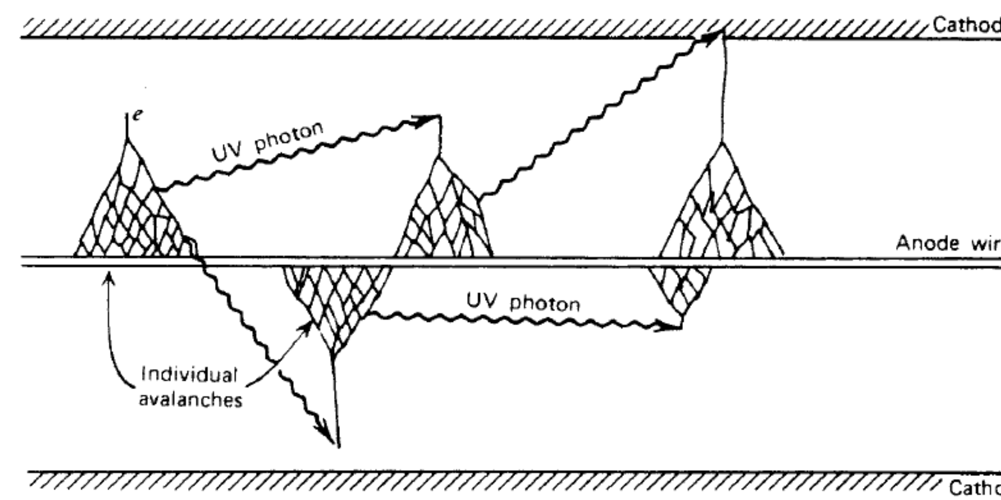
DETECTING IONISING RADIATION IN THE ENVIRONMENT: EXAMPLE

Geiger-Mueller counter: principle of operation

A Geiger-Mueller counter consists of a tube filled with an inert gas, such as argon or helium, at low pressure. When ionizing radiation enters the tube, it ionises the gas molecules along its path. This ionisation leads to the creation of free electrons and positively charged ions.

A high voltage is applied between a central wire (anode) and the outer metal tube (cathode). The electric field accelerates the free electrons. As the electrons travel towards the anode, they gain sufficient energy to create additional ionisation events through collisions with gas molecules along their path. This causes an avalanche effect, leading to a cascade of further ionisations. Moreover, from the cascades UV-photons are emitted and they can induce other avalanches as well.





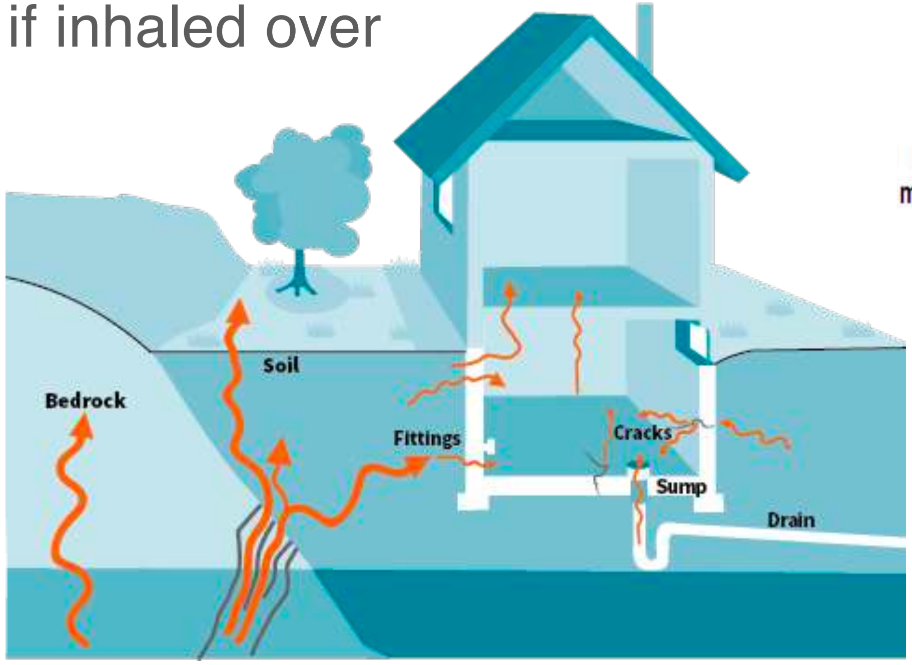
The Geiger counter is equipped with circuitry to detect and amplify these electrical pulses, producing an audible click or visual signal for each detected radiation event. The number of clicks or signals correlates with the intensity or rate of detected radiation.

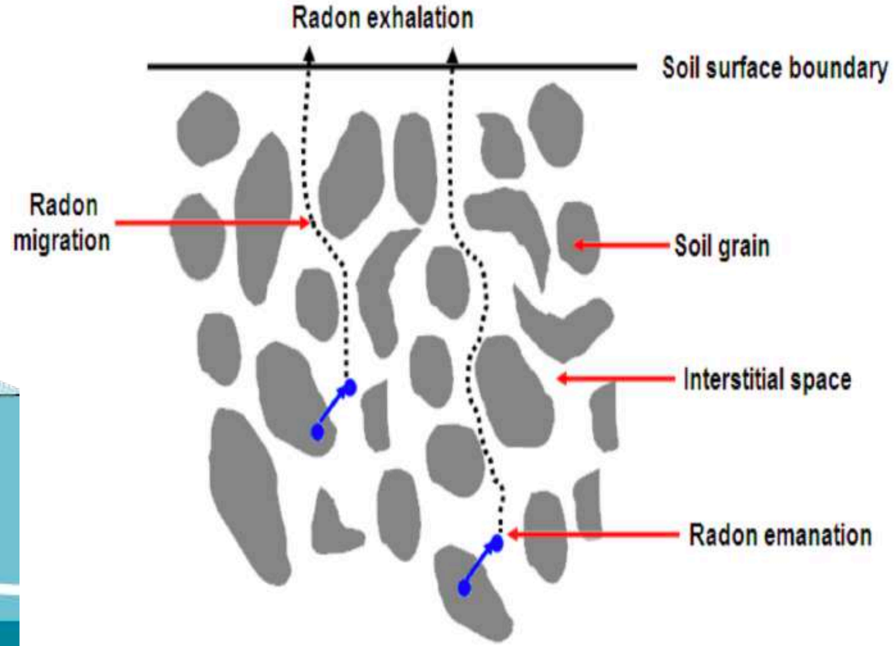
DETECTING IONISING RADIATION IN THE ENVIRONMENT: EXAMPLE

Radon monitor

A radon monitor operates on the principle of detecting and measuring the concentration of radon gas (222Rn) in the air. Radon is a naturally occurring radioactive gas that comes from the decay of uranium (238U). Radon gas is emanated in the environment from soil, water, rocks, building materials, etc.,.

Being 222Rn an alpha emitter with a short half life (3.8 days), the exposure to this gas poses health risks, specifically since it can accumulate in enclosed spaces, leading to increased risk of lung cancer if inhaled over extended periods.





http://dx.doi.org/10.5772/intechopen.69902

DETECTING IONISING RADIATION IN THE ENVIRONMENT: EXAMPLE

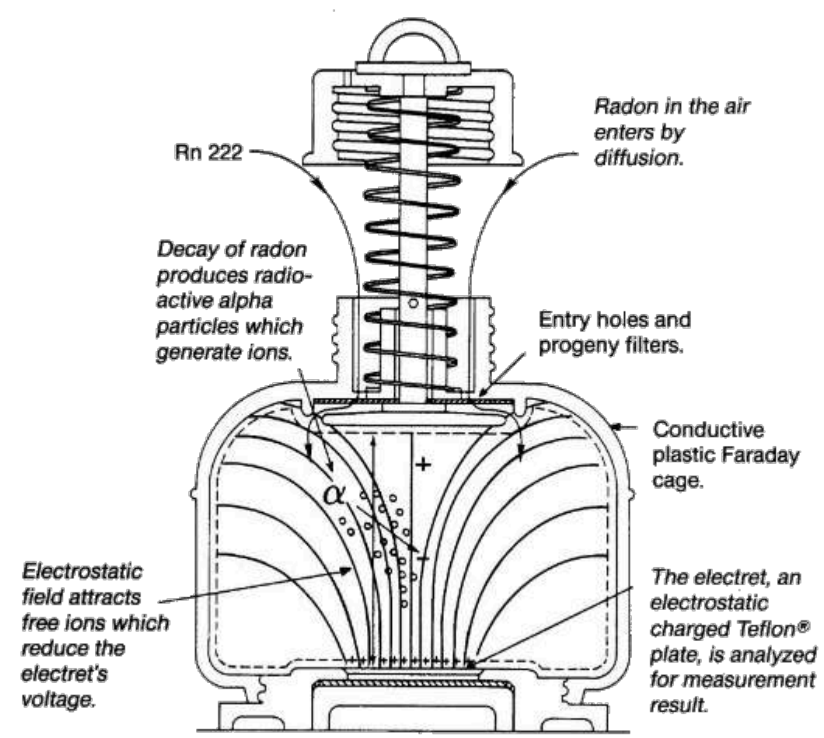
Radon monitor

There are various types of sensors and devices used for radon monitoring and detection.

- Active measurement methods:

Scintillation cells; Ionisation chambers; Electrostatic collection of decay products

- Passive measurement methods
    - *Charcoal detectors*: Activated charcoal has an affinity for many gases including radon. Radon adsorbed on charcoal will decay, and the decay products formed will be retained, allowing the adsorbed radon quantity to be measured via gamma spectrometry of the emissions from its daughters, Pb-214 and Bi-214
    - *Electret ion chambers*: These devices use an electrically charged Teflon disc (electret) to attract and measure the ions created by the decay of Rn and its decay products. The change in electrical charge due to ionisation is measured to determine radon levels.
    - *Etched track detectors*



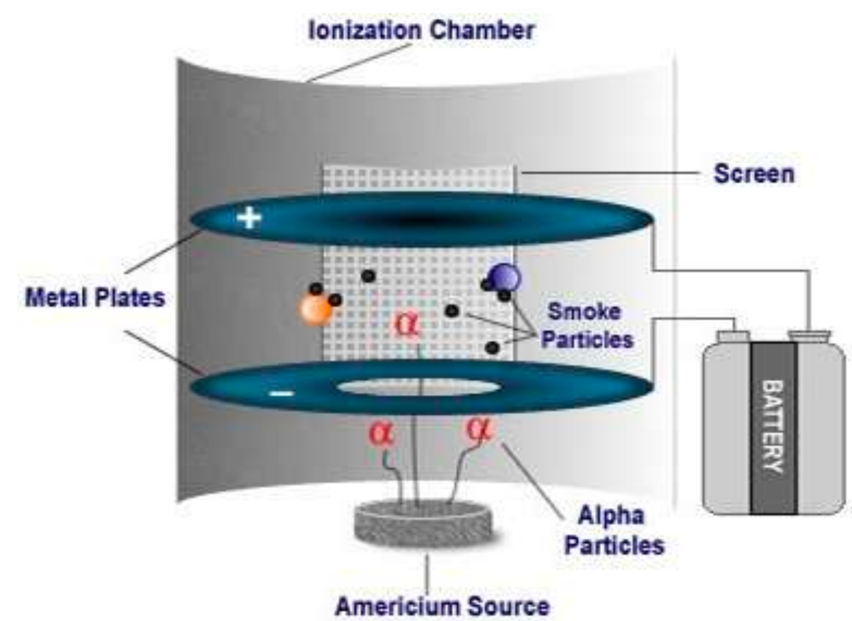
https://www.osti.gov/etdeweb/servlets/purl/20555902

DETECTING RADIATION IN THE ENVIRONMENT: EXAMPLE

Smoke sensor: ionisation detectors

The 'ionisation' smoke detectors use a small bit of safely shielded radioactive material (eg. 241Am source) that electrically charges, or ionises, the air molecules between two metal plates encapsulated in a ceramic holder. The radiation emitted by the reference source produces a small electric current flowing from one plate to the other in the air.

When particles (from smoke) enter the chamber, they attract the ions and carry them away, reducing the current. When the number of particles entering the chamber is enough to reduce that current below a certain amount, the device will register those particles as smoke and the alarm will sound.



https://www.nist.gov/how-do-you-measure-it/how-do-smoke-detectors-work

DETECTING RADIATION IN THE ENVIRONMENT: EXAMPLE

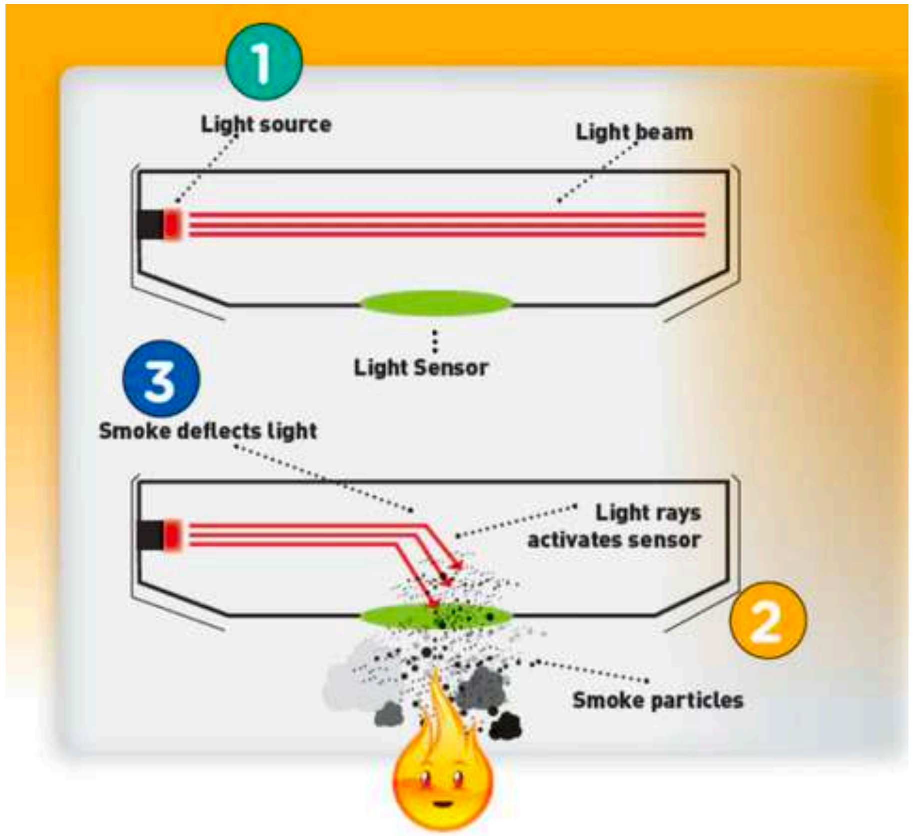
Smoke sensor: photoelectric detectors

The sensor has a chamber for light sensor inside it. This chamber has an LED light that shoots a beam of light in a straight line across the chamber.

When no (smoke) particles are present in the sensing chamber, the light from the beam does not strike the light detector, indicating all clear.

If smoke enters the chamber, it comes in the path of the straight line of the LED light and deflects it. When the straight LED light shifts its path, as deflected by the smoke, it enters into a photosensor in a different compartment of the same chamber.

When there are particles present and the amount of light registered by the light detector reaches a certain threshold level, the alarm sounds.



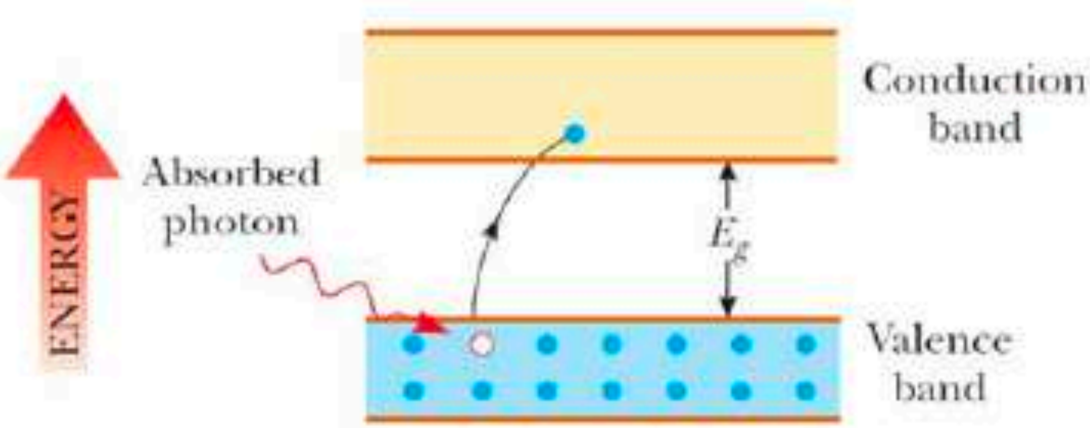
https://www.nist.gov/how-do-you-measure-it/how-do-smoke-detectors-work

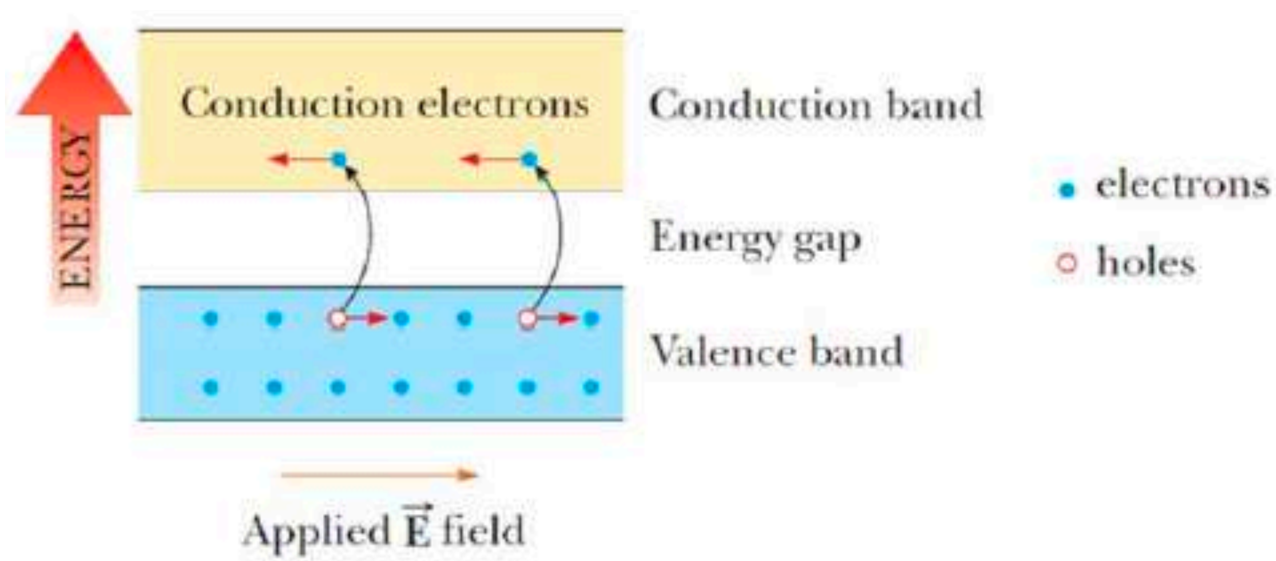
DETECTING NON-IONISING RADIATION

Detection of non-ionising radiation involves various methods depending on the specific frequency range of the radiation.

In case of EM radiation in the eV/keV-range (visible, IR, UV, X-ray), the detection involves the **conversion of photons into electrons**.

Photodetectors generally utilise a ***semiconductor*** material, such as silicon, germanium or gallium arsenide, which generates electron-hole pairs when exposed to photons. When photons strike the semiconductor material, they transfer their energy to electrons within the material, causing these electrons to move from the valence band to the conduction band, creating electron-hole pairs. This generation of electron-hole pairs results in a measurable electrical current or voltage, which can be detected and amplified, providing information about the incident radiation intensity.





DETECTING NON-IONISING RADIATION - LIGHT

Photosensors:

Among the different semiconductor photosensors, photodiodes, avalanche photodiodes, phototransistors and photovoltaic cells, are the most used ones in photon detection, particularly in optoelectronic applications.

Each of these devices offers unique features and performance characteristics tailored to specific applications, catering to a wide range of photon detection requirements in various fields, including telecommunications, imaging, remote sensing, and scientific research.

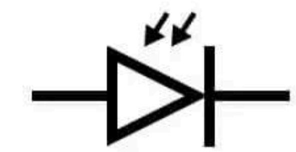
DETECTING NON-IONISING RADIATION - LIGHT

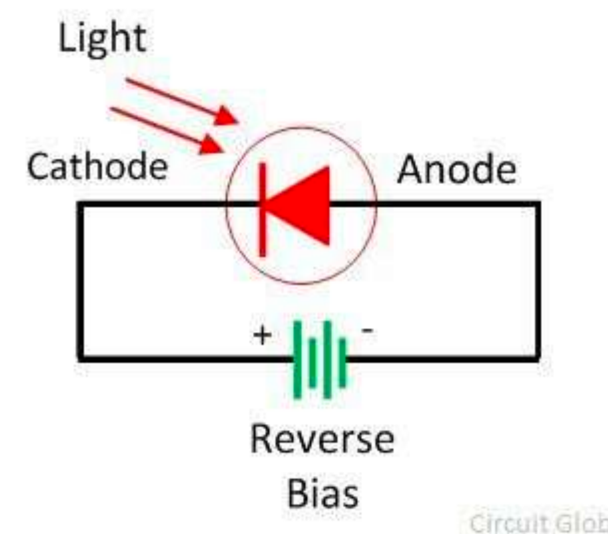
Photosensors:

1. **Photodiodes**:

- Principle: Photodiodes are semiconductor devices that convert light (photons) into electrical current. When photons strike the photodiode's light-sensitive semiconductor material (commonly silicon), they create electron-hole pairs, generating a flow of current in the device. This phenomenon occurs within the depletion region of the diode, where an external bias voltage creates an electric field that accelerates the charge carriers (electrons and holes) produced by incident photons.

- Operation: Photodiodes are used in various applications, including light detection, optical communications, and photometry. They are available in different types (PIN photodiodes, PN photodiodes) optimised for specific wavelength ranges and sensitivity requirements.





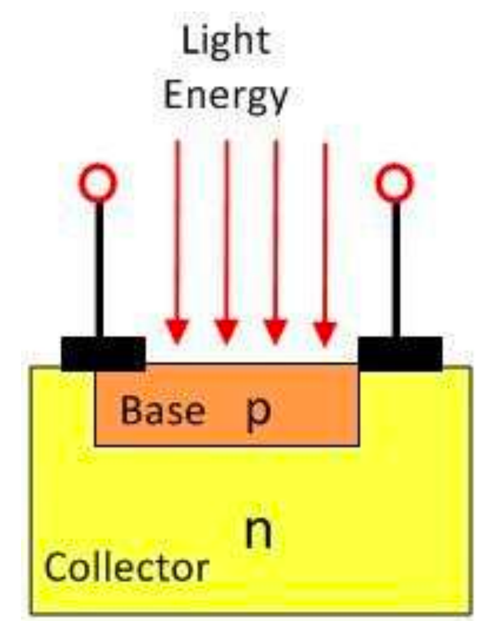
DETECTING NON-IONISING RADIATION - LIGHT

Photosensors:

2. **Phototransistors**:

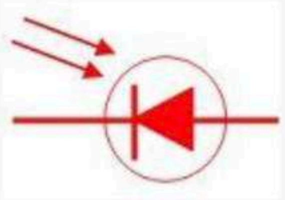
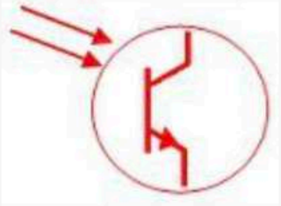
- Principle: Phototransistors are *transistors* designed to respond to light. They consist of a light-sensitive base region sandwiched between emitter and collector terminals. Incident photons in the base region generate electron-hole pairs, influencing the transistor's conductivity and resulting in an amplified current flow between the collector and emitter terminals.

- Operation: Phototransistors offer higher sensitivity and amplification compared to photodiodes, making them suitable for low-light applications in sensors, light meters, and optical switches.



DETECTING NON-IONISING RADIATION - LIGHT

Photosensors:

Basis For Comparison	Photodiode	Phototransistor
Definition	It is a type of PN-junction diode which generates electric current when light or photon is incident on their surface.	It is a type of transistor which converts the light energy into an electrical energy
Symbol		
Generates	Current	Current and Voltage
Output Response	Fast	Slow
Sensitivity	Less	More
Biasing	Both forward and reversed biasing.	Forward biasing (emitter is more negative as compared to the collector.)
Uses	For generating solar power, for detecting ultraviolet or infrared rays, for measuring light etc.	Smoke detector, compact disc players, invisible light receiver, in laser etc.

https://circuitglobe.com/difference-between-photodiode-and-phototransistor.html

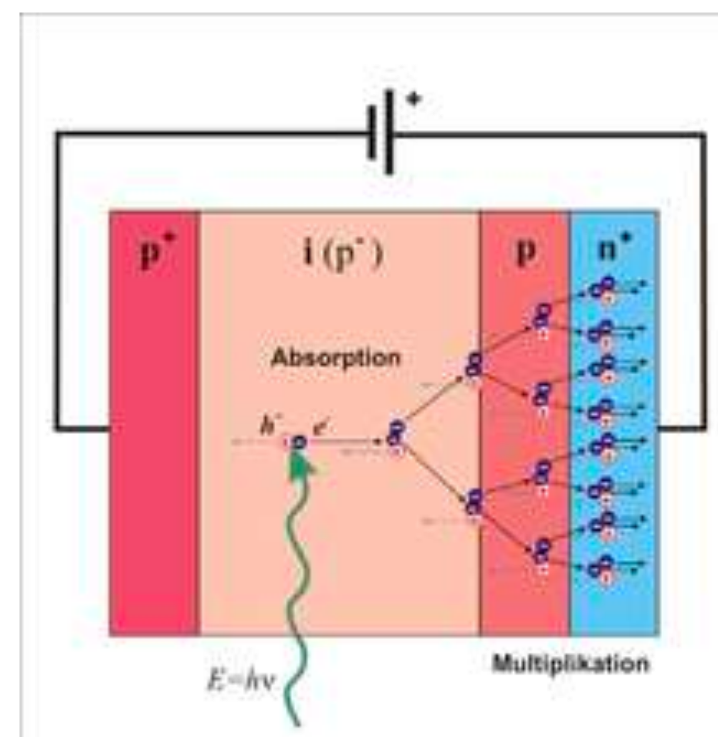
DETECTING NON-IONISING RADIATION - LIGHT

Photosensors:

3. **Avalanche Photodiodes** (APDs):

- Principle: Avalanche photodiodes are specialised photodiodes operating in the avalanche breakdown region. They exhibit *internal multiplication* of charge carriers through impact ionisation. When photons strike the APD, they create electron-hole pairs, and under a high reverse bias voltage, these carriers gain sufficient energy to generate additional carriers through impact ionisation, leading to an avalanche effect, significantly amplifying the initial photocurrent.

- Operation: APDs provide extremely high sensitivity and gain compared to standard photodiodes, making them ideal for applications requiring detection of weak optical signals, such as high-speed telecommunications, LIDAR (Light Detection and Ranging), and scientific instrumentation.



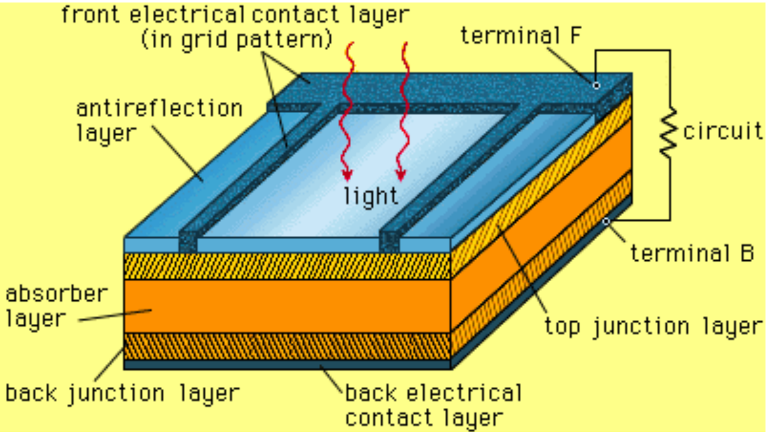
DETECTING NON-IONISING RADIATION – LIGHT

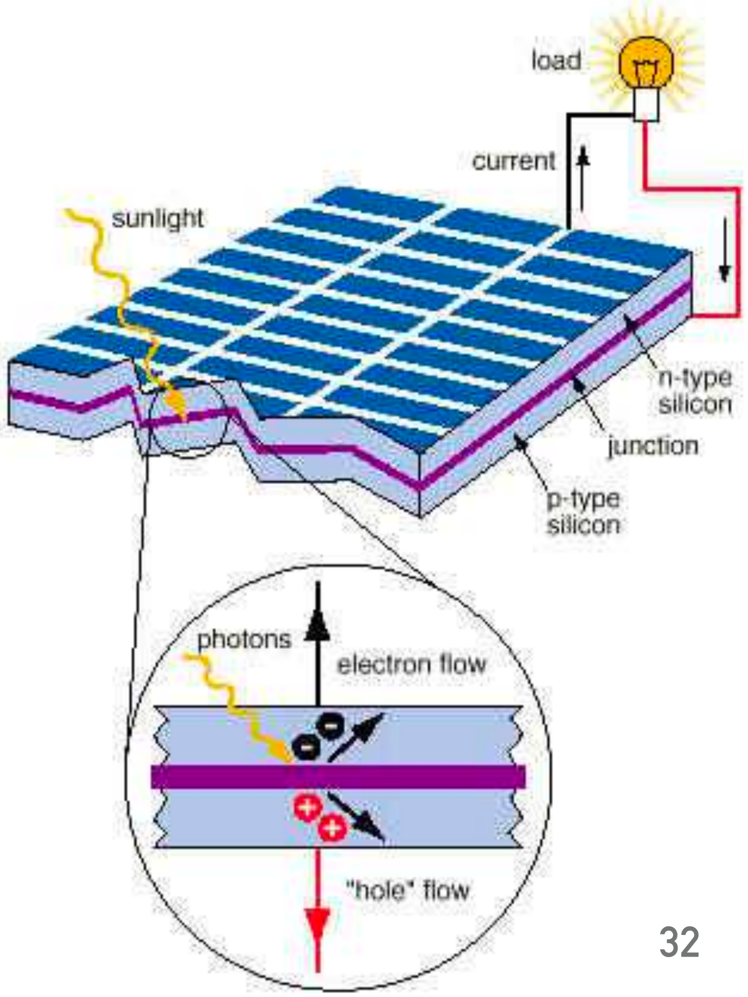
Photosensors:

4. **Solar/Photovoltaic cells**:

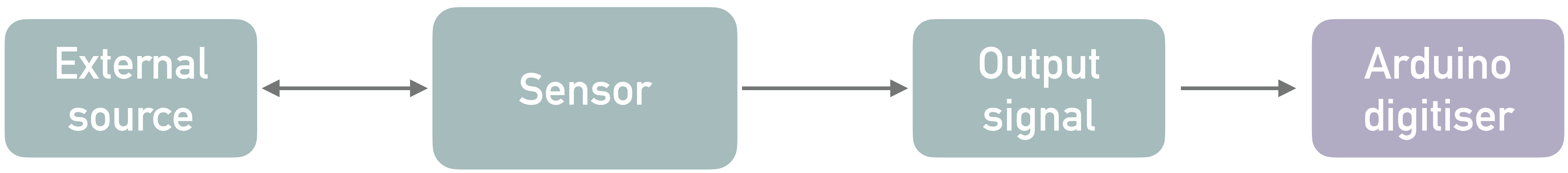
- Principle: Solar cells utilise the photovoltaic effect to convert (visible/UV) light energy into electricity. They are typically made of semiconductor materials, such as crystalline Si, thin-film materials (like CdTe or amorphous Si), or emerging materials like perovskites. These materials have a *built-in electric field* due to the p-n junction structure or hetero-junctions within the cell.

- Operation: When photons from sunlight strike the solar cell's semiconductor material, they create electron-hole pairs. The built-in electric field within the solar cell separates these charge carriers, causing the electrons to flow as an electric current which is the output of the solar cell. Solar cells are integral components of renewable energy systems. Ongoing advancements in solar cell technologies aim to improve efficiency, reduce costs, and expand their deployment





EXAMPLE: LIGHT DETECTION WITH A PHOTOSENSOR



- Source: Ambient light / LED
- Sensor: Phototransistor
- Read the signal output: Arduino digitiser

See Lab.4

BACKUP

SENSING THE ENVIROMENT

- Sources
  - Temperature & pressure: sensors & platforms
  - Distance and position: us, laser, gps —> lab: exp us
  - Speed: wind speed, antropic speed —> lab: exp accelerometers (ex automatic drive)
  - Vibrations: seismos —>
  - Acoustic —> lab: exp mics
  - Radiations: particle () & light (energy) —> lab: show cont geiger, and photodiodes or solar cell