Introduction to Medical Imaging
Part II

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Ultrasound imaging

- It exploits **ultrasound waves** (frequency: [1,10] MHz; wavelength: [0.1,1] mm)
- It operates in **reflection mode**, i.e., it measures the waves reflected by the tissue of interest

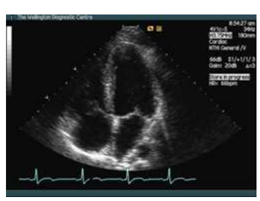
Ultrasound imaging

- It exploits **ultrasound waves** (frequency: [1,10] MHz; wavelength: [0.1,1] mm)
- It operates in **reflection mode**, i.e., it measures the waves reflected by the tissue of interest
- It is used because
  - ***It does not require radiation exposure***
  - ***It is non-invasive and safe***
  - ***It is fast and (relatively) inexpensive***

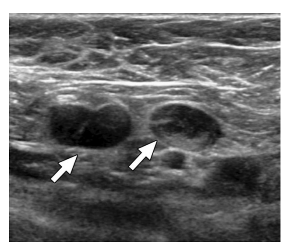
Ultrasound imaging

- Typical applications include fetus and heart monitoring, and screening for tumors

fetus monitoring



heart monitoring

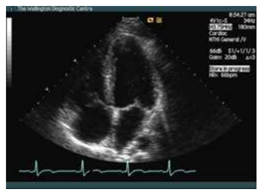


detection of malignant breast tumors

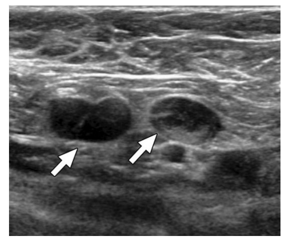
Ultrasound imaging

As suggested by the figures, resolution is usually low (> 1mm) and contrast is limited

fetus monitoring

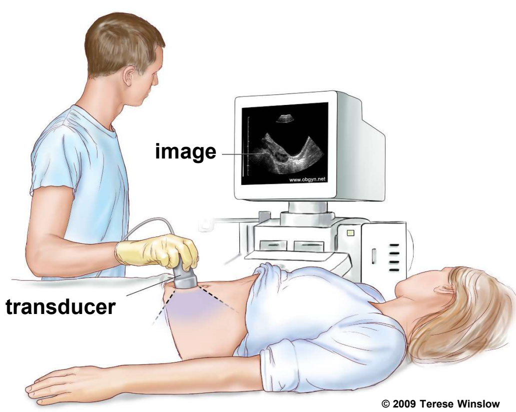


heart monitoring

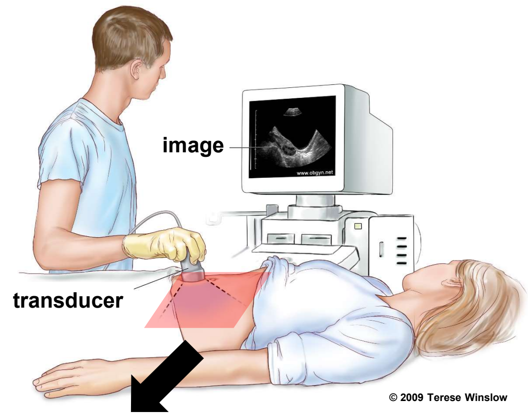


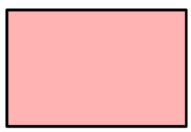
detection of malignant breast tumors

A typical ultrasound setup



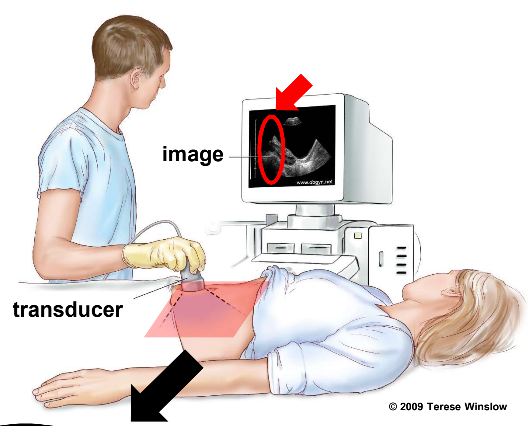
A typical ultrasound setup

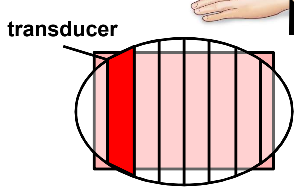




1) **Consider the scanned skin surface as a 2-D plane: for every point covered by the transducer, an image of the tissue underneath is recreated on screen**

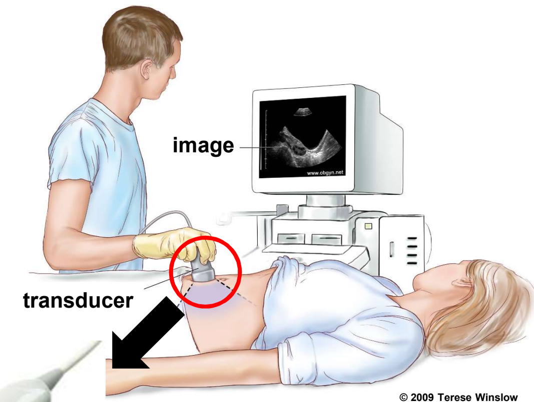
A typical ultrasound setup





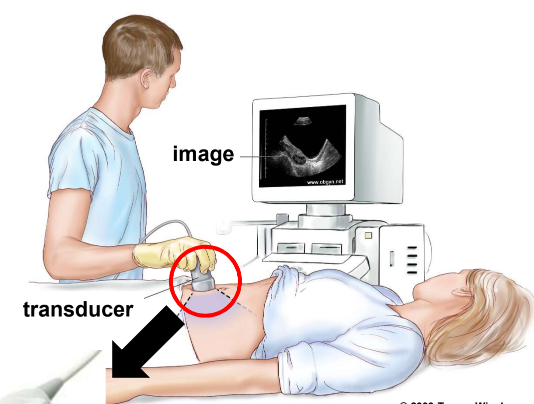
1) **Consider the scanned skin surface as a 2-D plane: for every point covered by the transducer, an image of the tissue underneath is recreated on screen**

A typical ultrasound setup



2) The transducer is a device that converts electrical signals into acoustic waves (<u>like a speaker</u>)

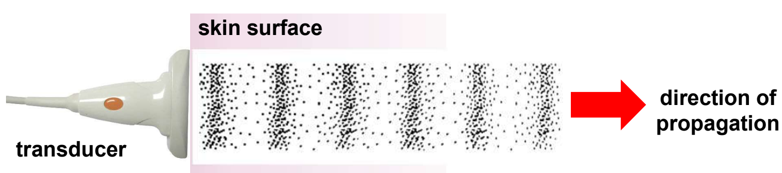
A typical ultrasound setup



3) The transducer also works as a receiver, i.e., it collects acoustic waves and converts them into electric signals (<u>like a microphone</u>)

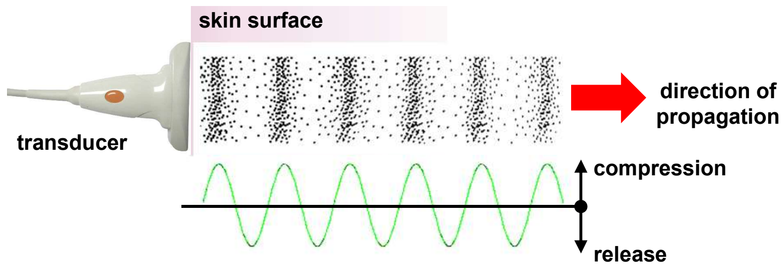
Ultrasound waves

Ultrasound waves



- ❑ Ultrasound waves propagate through the skin by compressing and releasing small volumes of tissue

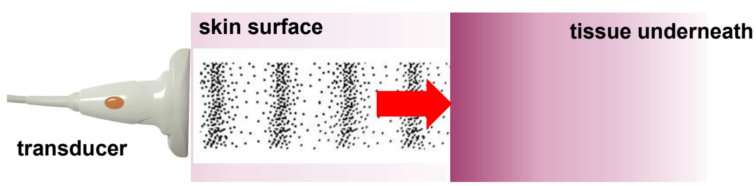
Ultrasound waves



❑ Ultrasound waves propagate through the skin by compressing and releasing small volumes of tissue

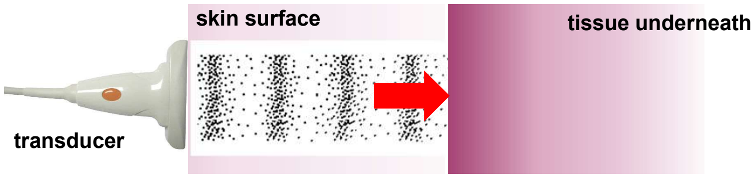
❑ Molecules in the tissue move back and forth in the same direction the wave is traveling

Ultrasound waves



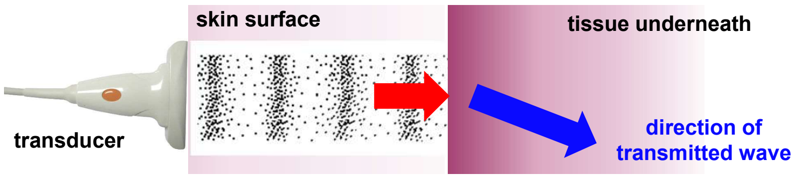
❑ Let us suppose that the wave hits another layer of tissue (e.g., muscle, bone, or fat, etc.)

Ultrasound waves



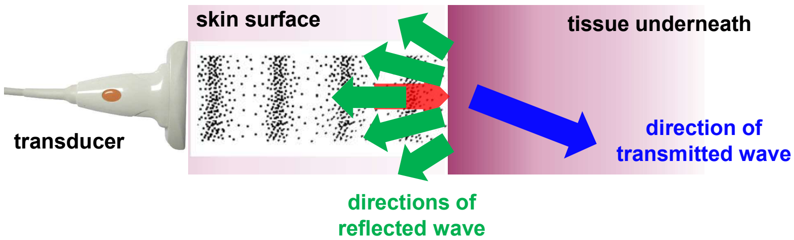
- Let us suppose that the wave hits another layer of tissue (e.g., muscle, bone, or fat, etc.)
- The density of matter varies with the tissue and it is different from the superficial skin layer

Ultrasound waves: echo



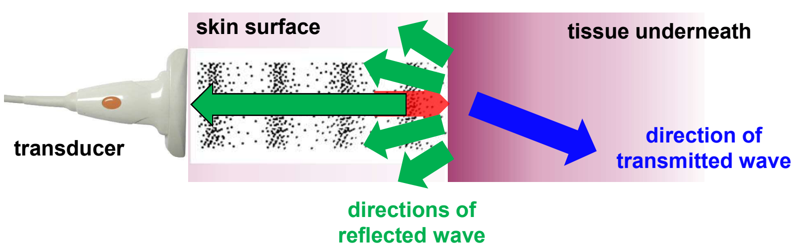
- As a result, the wave will propagate in the new tissue but with lower amplitude (less intensity) and a different direction (**refraction**)

Ultrasound waves: echo



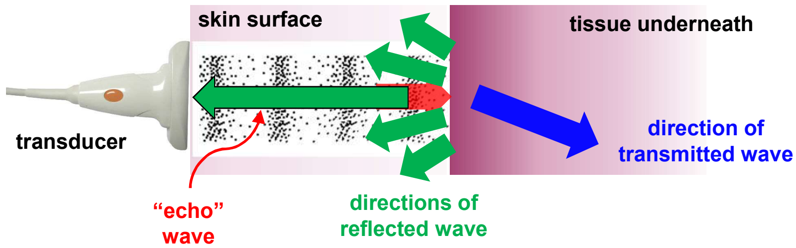
- As a result, the wave will propagate in the new tissue but with lower amplitude (less intensity) and a different direction (**refraction**)
- The wave will be in part reflected (**scattering**), i.e., a wave will propagate backward within the original tissue along **multiple directions**

Ultrasound waves: echo



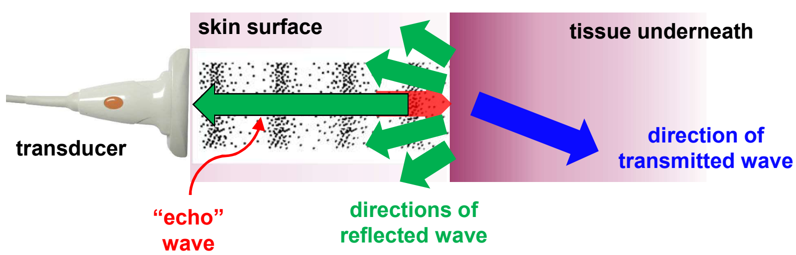
- At least one of the reflected waves will hit back the transducer (a phenomenon called **"echo"**)

Ultrasound waves: echo



- ❑ Two aspects characterize the echo wave:
  - **Delay** (since the emission of the source wave from the transmitter)
  - **Intensity** (energy transported by the echo wave per cycle)

Ultrasound waves: echo



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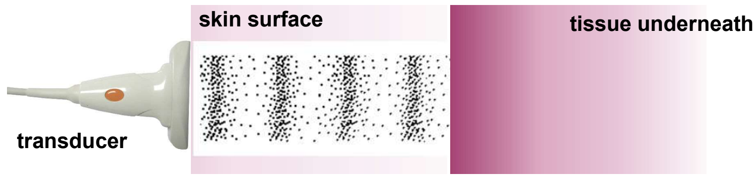
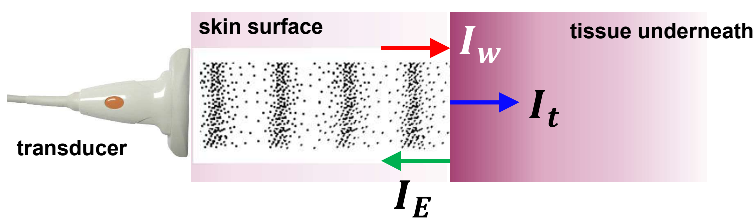
The image depends on both

Intensity of the echo wave



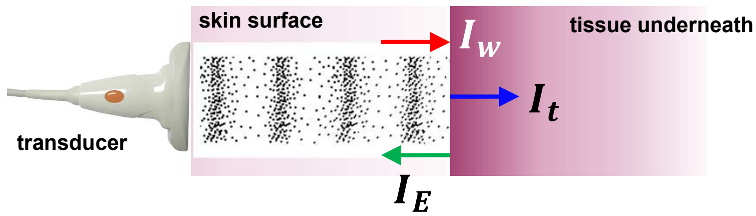
- The **intensity** of the echo wave depends on the two tissues that form the interface

Intensity of the echo wave



- The **intensity** of the echo wave depends on the two tissues that form the interface
- Let us call I_w, I_t, I_E the intensity of the emitted wave, the wave transmitted to the second tissue, and the echo wave, respectively

Intensity of the echo wave



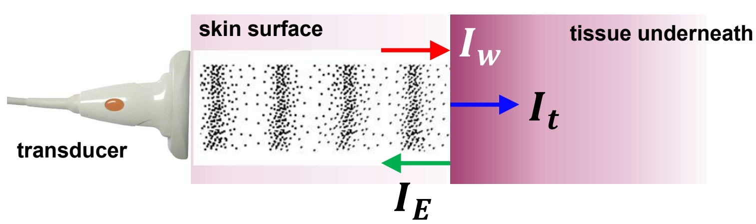
- It can be shown that:

$$I_E = R \times I_w$$

$$I_t = (1 - R) \times I_w$$

$$0 < R < 1$$

Intensity of the echo wave



- It can be shown that:

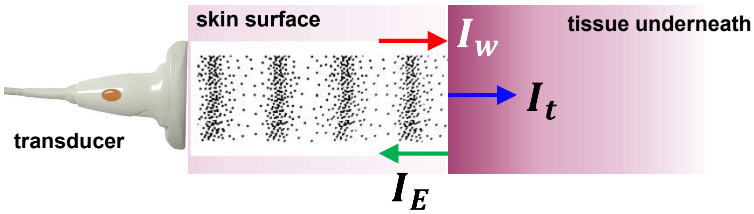
reflection coefficient

$$I_E = R \times I_w$$

$$I_t = (1 - R) \times I_w$$

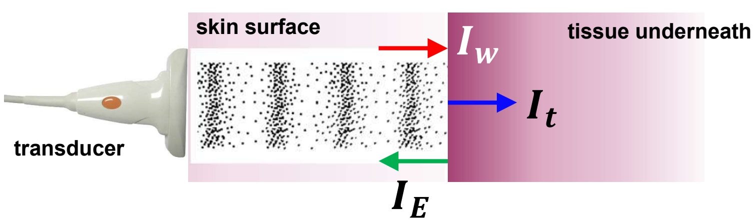
$$0 < R < 1$$

Acoustic impedance



- Every tissue opposes to the propagation of waves through it
- Therefore, the wave amplitude decreases as it moves forward within the tissue (**attenuation**)

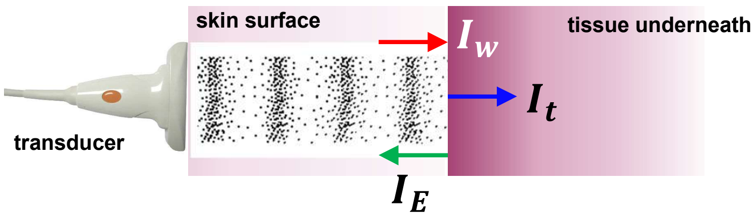
Acoustic impedance



- Every tissue opposes to the propagation of waves through it
- This opposition is quantified by the **acoustic impedance** (Z), which is defined as

$$Z = v \times \rho$$

Acoustic impedance



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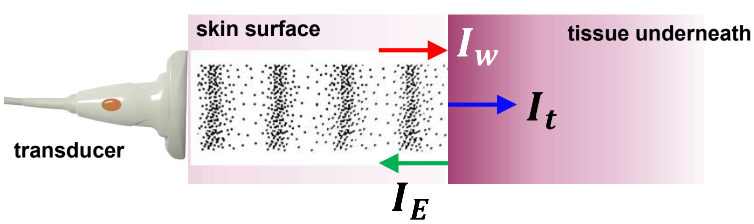
tissue density

Acoustic impedance



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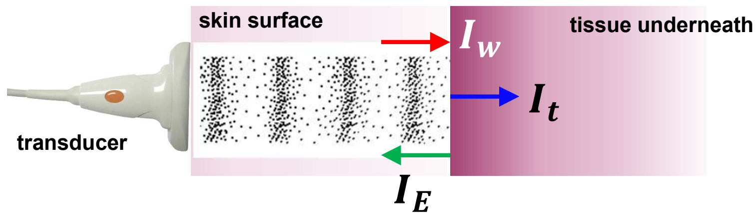
velocity of the wave in the tissue

$$Z = v \times \rho$$

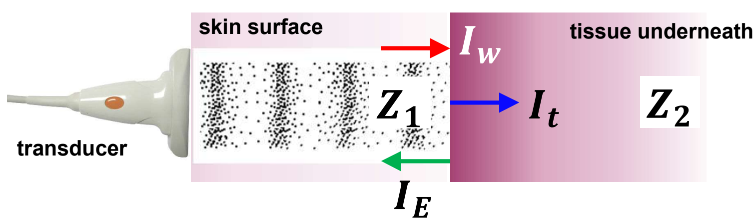
Acoustic impedance



❑ Impedance $\boldsymbol{Z}$ is measured in "Rayl":

1 Rayl = 1 kg/m^3 x 1 m/s

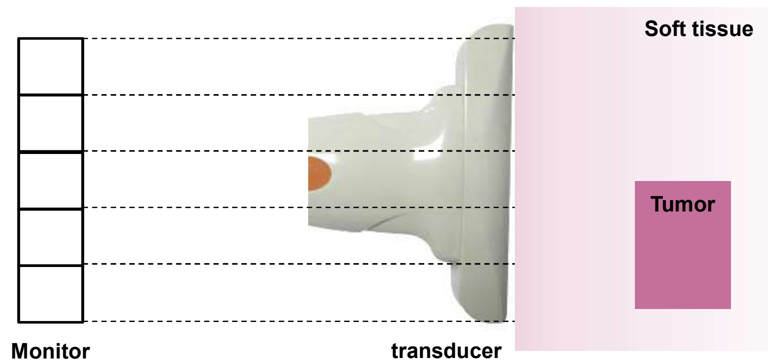
Acoustic impedance



❑ The reflection coefficient $\boldsymbol{R}$ is:

$$\boldsymbol{R} = \left(\frac{\boldsymbol{Z}_2 - \boldsymbol{Z}_1}{\boldsymbol{Z}_1 + \boldsymbol{Z}_2}\right)^2$$

An intuition of how the system works



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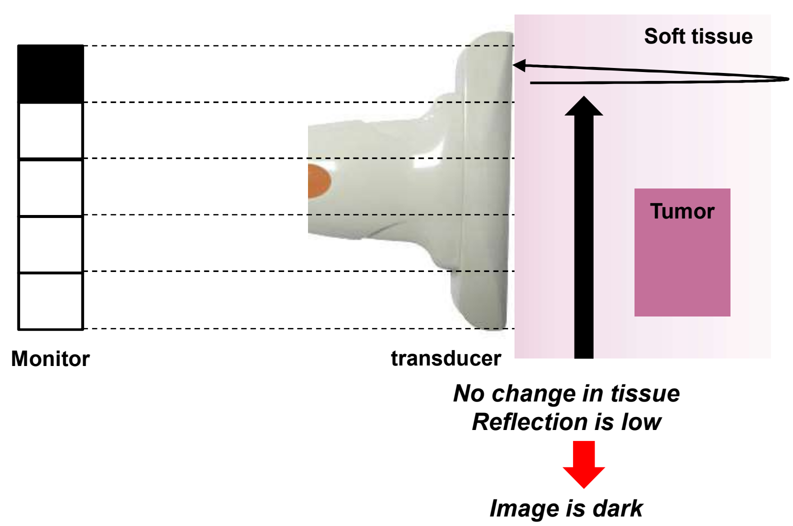

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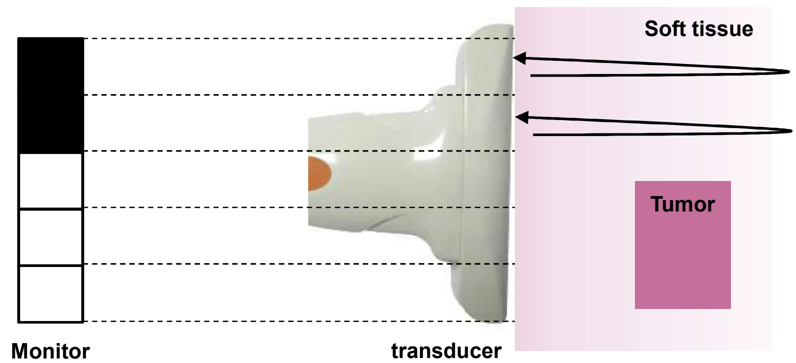

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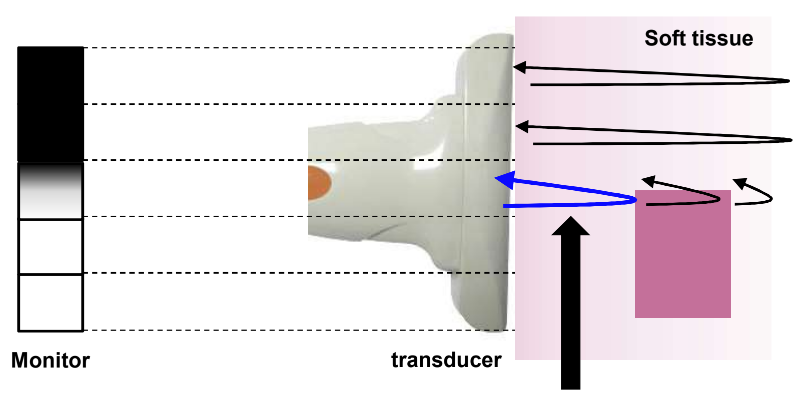
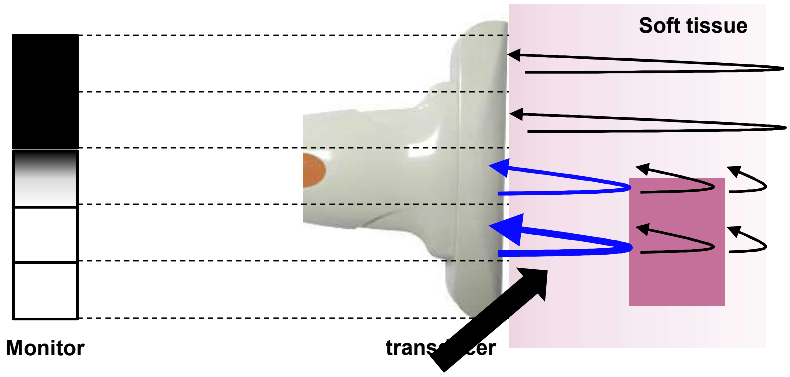


We are at the border of the tumor mass
Reflection is higher (R is closer to 1)
Delay for the echo wave is shorter

Image becomes brighter

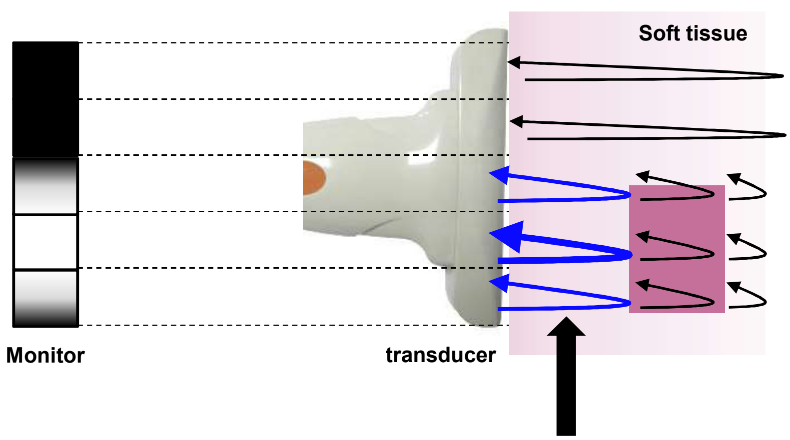
An intuition of how the system works



We are right on top of the tumor mass
Echo wave has even higher intensity

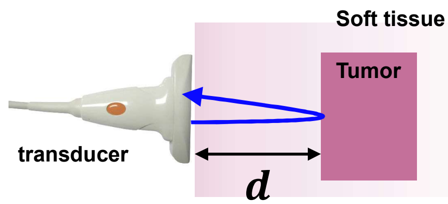
Image becomes very bright

An intuition of how the system works



We are now onto the other border of the tumor mass

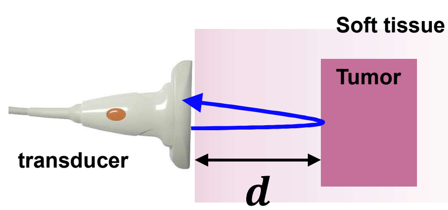
Example 1



- The wave pulse emitted by the transducer travels in soft tissue with velocity v_{st} = **1540 m/s**
- The echo wave is received t = **50 μs** after the emission of the wave pulse

How deep is the tumor?

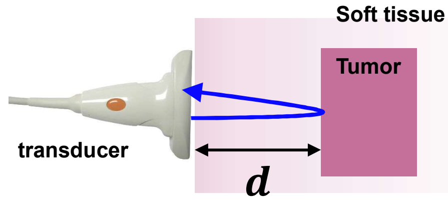
Example 1



- During the time t, the wave pulse has covered the distance d (unknown) two times (i.e., forward and backward) with velocity v_{st}

$$v_{st}t = 2d \Rightarrow d = \frac{1}{2}v_{st}t = \frac{1540 \times 50 \times 10^{-6}}{2}$$
$$= 0.0385 \text{ m} = 38.5 \text{ mm}$$

Example 2



- The intensity of the reflected wave is 1% of the emitted wave and the soft tissue is mostly made of fat

What is the acoustic impedance of the tumor?

Example 2

Body tissue	Acoustic Impedance (10^6 Rayls)
Lung	0.18
Fat	1.34
Liver	1.65
Blood	1.65
Kidney	1.63
Muscle	1.71
Bone	7.8

$$Z_{st} = Z_{fat} = 1.34 \times 10^6 \text{ Rayl}$$

$$Z_{tumor} = ?$$

st = soft tissue

Example 2

Body tissue	Acoustic Impedance (10^6 Rayls)
Lung	0.18
Fat	1.34
Liver	1.65
Blood	1.65
Kidney	1.63
Muscle	1.71
Bone	7.8

$$R = 0.01 = \left(\frac{Z_{tumor} - Z_{fat}}{Z_{fat} + Z_{tumor}}\right)^2 \Rightarrow Z_{tumor} = \frac{1.1}{0.9} Z_{fat}$$
$$= 1.64 \times 10^6 \text{Rayl}$$

Radiography

- It exploits **electromagnetic waves** (**X-rays**, wavelength: [0.1,1] nm*, frequency: $3\text{x}10^{16}$ Hz to $3\text{x}10^{19}$ Hz)
- It operates in **transmission mode**, i.e., it measures the waves that pass through the tissue of interest and reach a target

*nm $\stackrel{\text{def}}{=}$ 10^{-9} m

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- It operates in **transmission mode**, i.e., it measures the waves that pass through the tissue of interest and reach a target
- The target is a 2-D surface, i.e., the image is a **projection** of the tissue of interest

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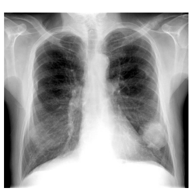
Applications of radiography

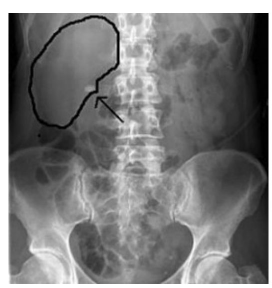
- Typical applications include structural imaging of bones (to diagnose fractures) and soft tissue (to diagnose perforation, stones, cancer mass, etc.)



lungs

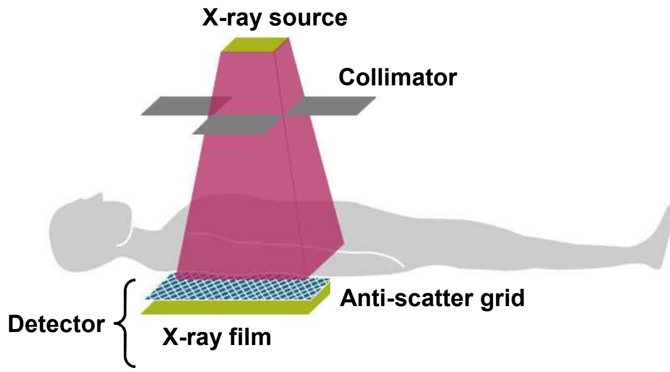
bones

teeth

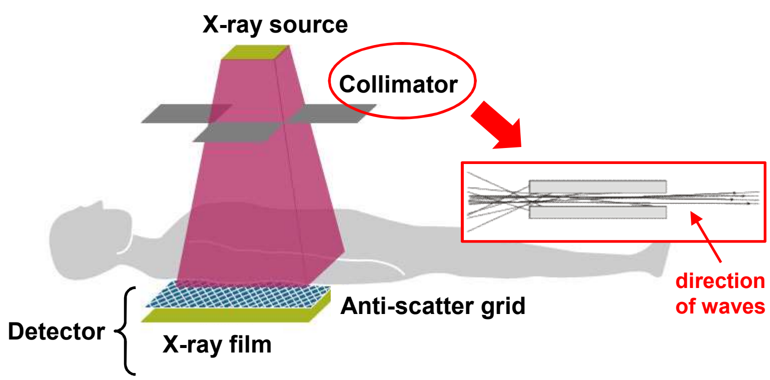


kidney

A typical radiography setup

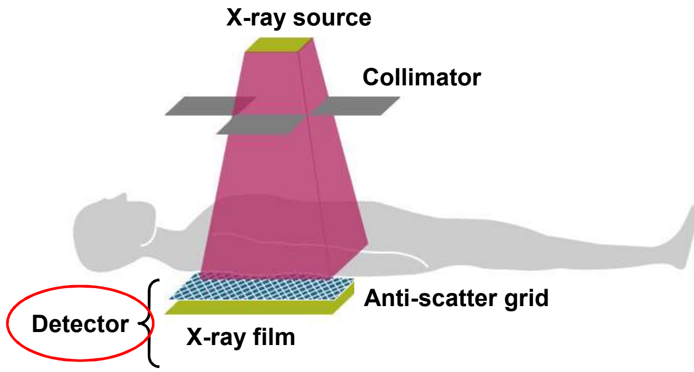


A typical radiography setup



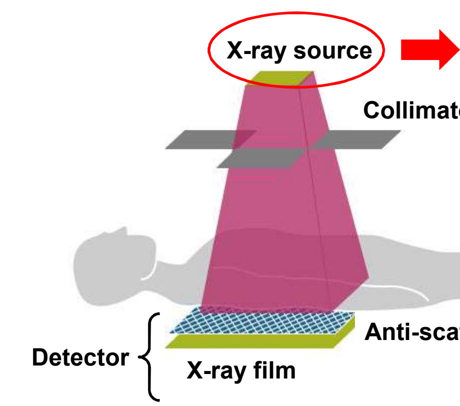
The collimator makes the directions of the waves more aligned in a specific direction

A typical radiography setup



*Waves are converted in light and form a **"shadow"** image on the film. This image reflects variations in transmission due to structures of different thickness, density, or composition*

A typical radiography setup

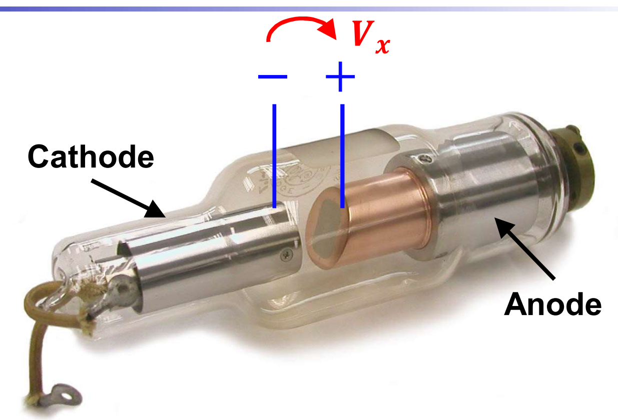


*The source consists of an **X-ray tube**, which generates X-rays by releasing electrons against a plate made of tungsten*

X-ray tube

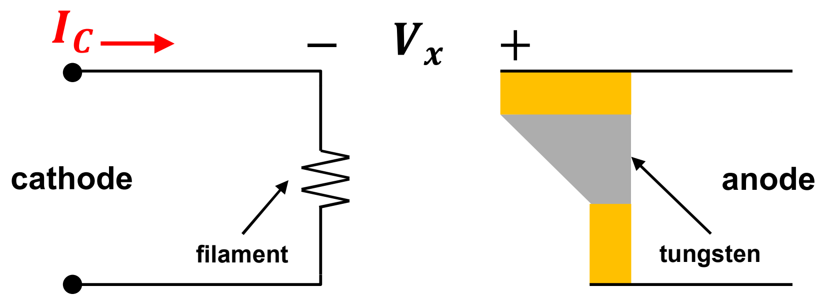
The X-ray tube uses electric currents and voltages to generate X-rays

X-ray tube



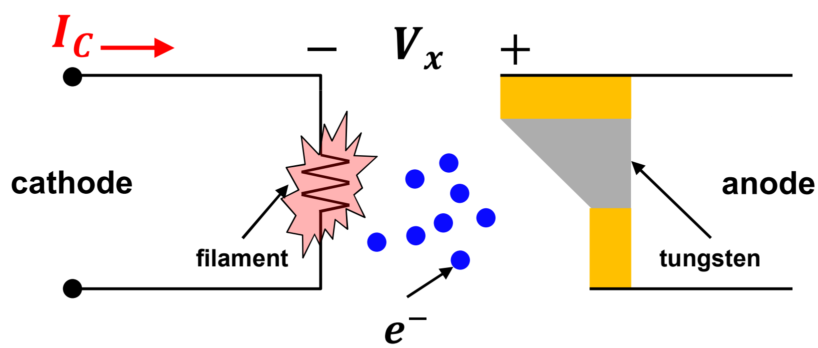
First, a high voltage difference (V_x~30-150 kV) is applied between anode and cathode across an empty junction

X-ray tube



Second, a current I_C (0.01-1 A) flows in the cathode and heats a filament, which then releases electrons (e^-) in the junction

X-ray tube



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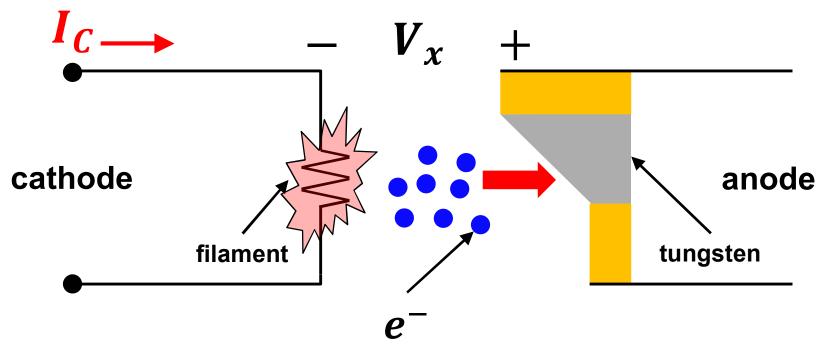
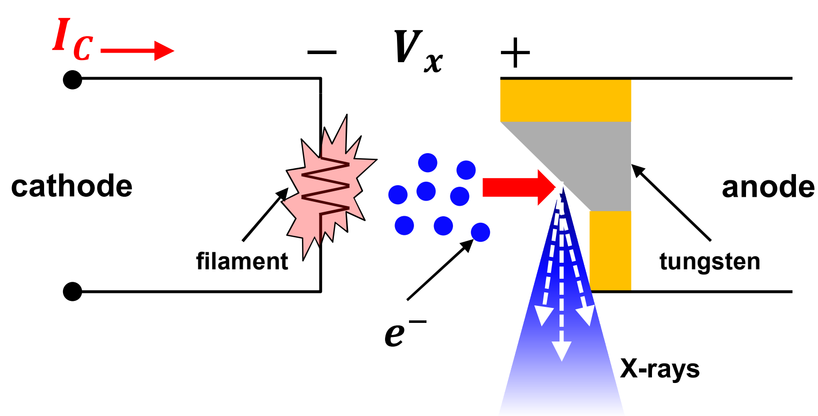


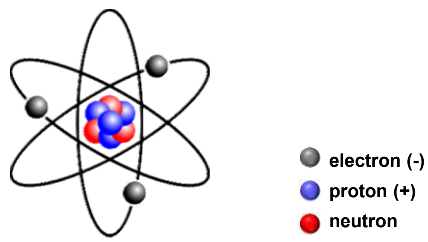
Third, because of the high voltage V_x, electrons are steered toward the tungsten plate on the anode

X-ray tube



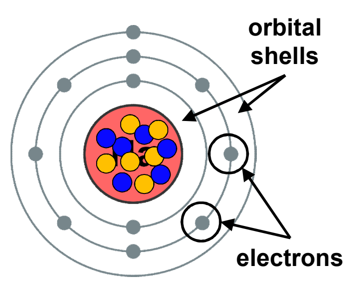
When hit by the electrons, the tungsten atoms emit X-rays with an angle that facilitates the propagation outside the tube

Emission of X-rays: background



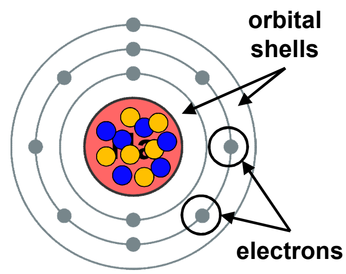
- An electron is an atomic particle with **negative charge** ($e^- \cong -1.6 \times 10^{-19}$ C)
- Electrons move around the nucleus along orbital shells

Emission of X-rays: background



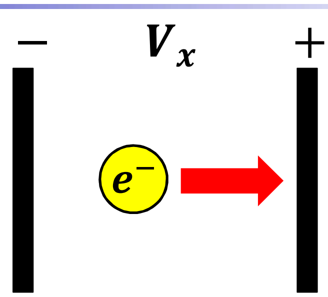
- An orbital shell can host only a **finite** number of electrons
- Electrons fill in the orbital shells **closest** to the nucleus first

Emission of X-rays: background



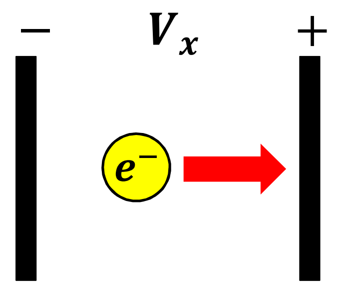
- The **closer** the shell to the nucleus, the **lower** the energy of the shell's electrons
- An electron has the **highest energy** when it is **not bounded** to any orbital shell (it is free to move away)

Emission of X-rays: background



- The energy of an electron is measured in **electron-volts (eV)**
- 1 eV is the energy that an electron has when freely moving across a voltage of 1 V

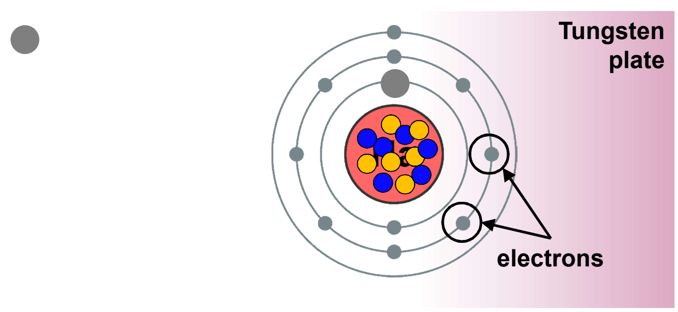
Emission of X-rays: background



- The energy of an electron is measured in **electron-volts (eV)**

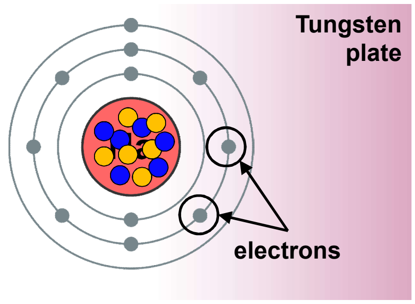
$$\mathbf{1\ eV} \stackrel{\text{def}}{=} \mathbf{1}\ \boldsymbol{e^-} \times \mathbf{1\ V} \cong \mathbf{1.6} \times \mathbf{10^{-1}} \quad \mathbf{J}$$

Emission of X-rays



A free moving electron hits on a tungsten atom and “knocks” one of the electrons out of the atom, i.e., it transfers enough energy to this electron to make it unbounded

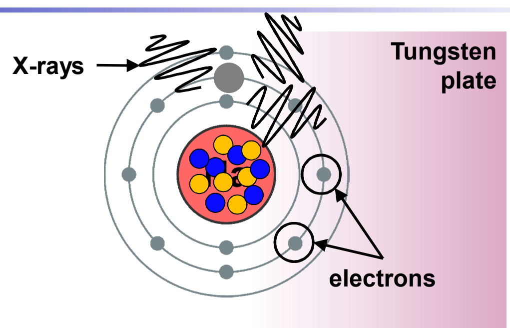
Emission of X-rays



The average energy that is needed to "knock" one of the electrons depends on the material

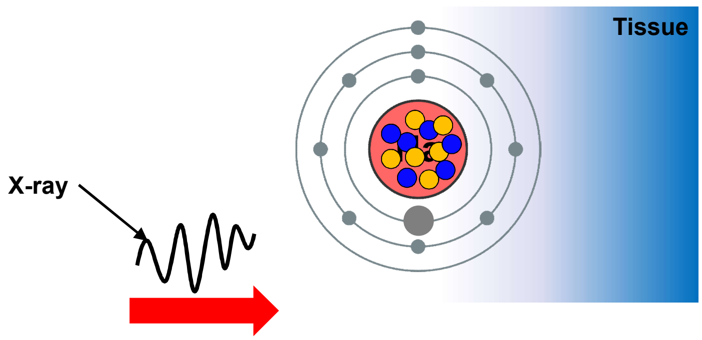
- Hydrogen = 13.6 eV
- Air: 29 eV
- Lead: 1 KeV
- **Tungsten: 4 KeV**

Emission of X-rays



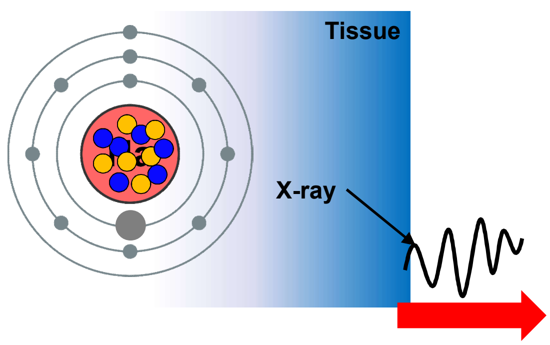
Another electron from an outer orbital shell moves to the inner shell to fill in the vacancy and – doing so – it releases energy in the form of X-rays

Propagation of X-rays



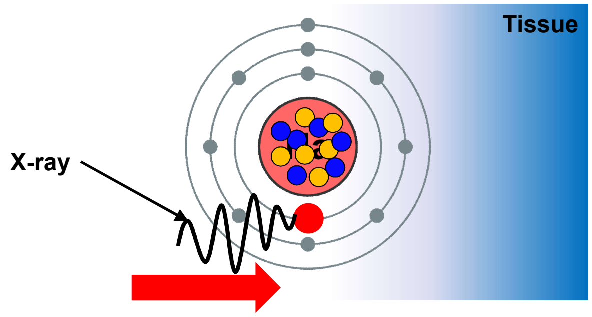
Now let us assume that a beam of X-rays has left the X-ray tube and reaches a target tissue (e.g., bones, lungs, etc.)

Propagation of X-rays



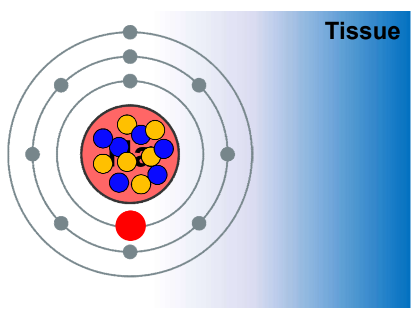
Option 1: The X-ray does not interact with atoms and manages to propagate through the tissue and to reach the other side

Propagation of X-rays



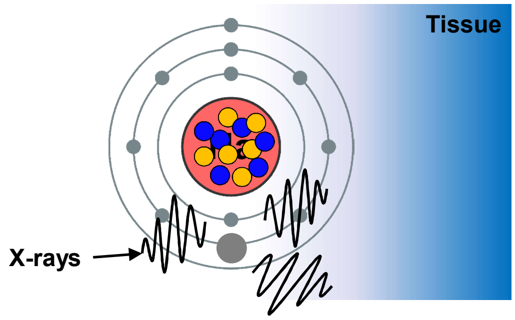
Option 2: The X-ray hits an atom. The X-ray will be absorbed and its energy will be transferred to the electron in the inner shell

Propagation of X-rays



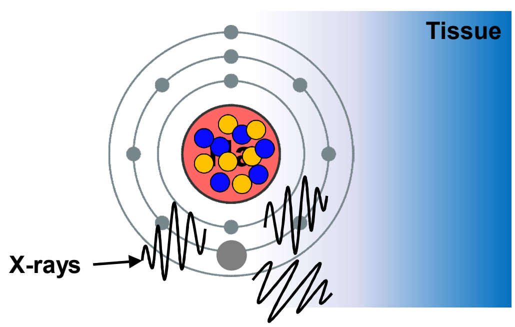
As a result, the electron receiving energy will move away from the atom (**ionization**) …

Propagation of X-rays



… and another electron from an outer shell will move to the inner shell, thus releasing new X-rays in various directions…

Propagation of X-rays



… which means that the original X-ray beam did not reach the other side of the tissue, i.e., **the X-ray did not pass through the tissue**

In practice…

- **Option 1** (passing through) happens more often when the tissue is made of atoms with a **low number of protons** (e.g., soft tissue, which is largely made of water)

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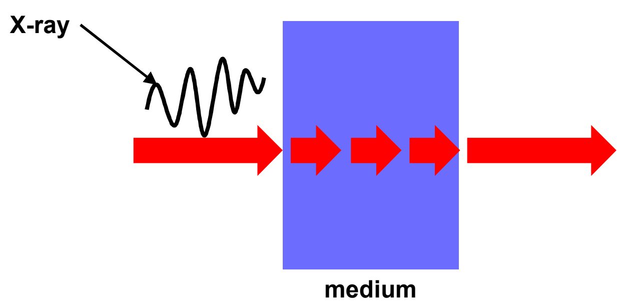
↓

That's why bones are so clearly identifiable in an X-ray image

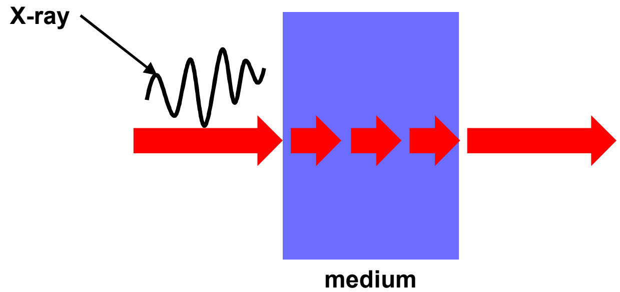
X-ray attenuation

- Let us assume that a medium (e.g., tissue) let the X-rays pass through



X-ray attenuation

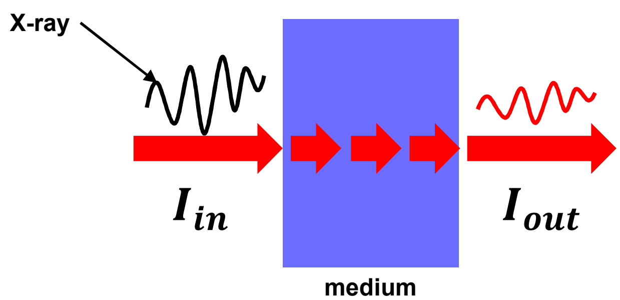
- Let us assume that a medium (e.g., tissue) let the X-rays pass through
- The medium will oppose to the passage of the wave



X-ray attenuation

- As a result, the energy of the X-ray will be attenuated by the medium

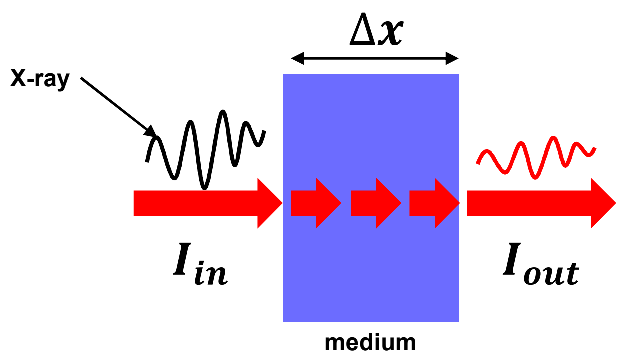
$$I_{out} = R \times I_{in}$$
$$0 < R < 1$$



X-ray attenuation

- The attenuation depends on the thickness of the medium

$$R = e^{-a_m \rho \Delta x}$$



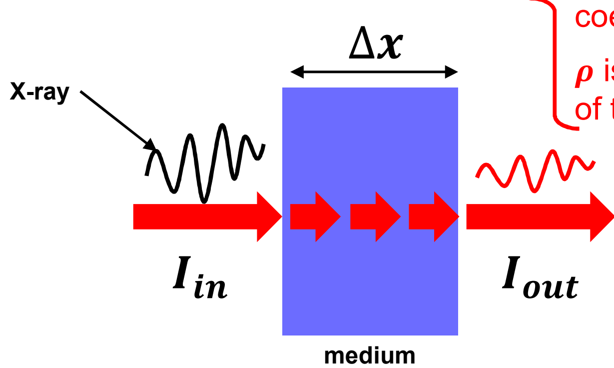
X-ray attenuation

- The attenuation depends on the thickness of the medium

$$R = e^{-a_m \rho \Delta x}$$

a_m is the attenuation coefficient

ρ is the density of the material



Example 3

An X-ray with energy $\boldsymbol{I_{in}}$ =140 keV passes through an apron made of lead ($\boldsymbol{a_m}$ = 2.0 cm^2/g; ρ =11.3 g/cm^3) with $\Delta\boldsymbol{x}$ =0.1 cm

How much is $\boldsymbol{I_{out}}$?

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$$\boldsymbol{I_{out} = e^{-a_m \rho \Delta x} I_{in}}$$

⬇

$$\boldsymbol{I_{out} = e^{-2\times 11.3\times 0.1}} \times \boldsymbol{140 = 14.6} \text{ keV}$$

Example 4

How much should Δx be to obtain $\boldsymbol{R}$ =0.8?

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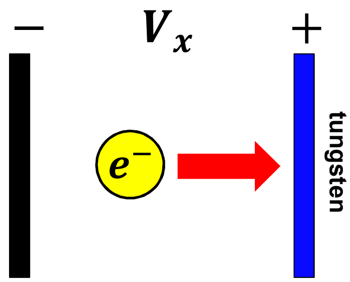
$$R = e^{-a_m \rho \Delta x}$$

⬇

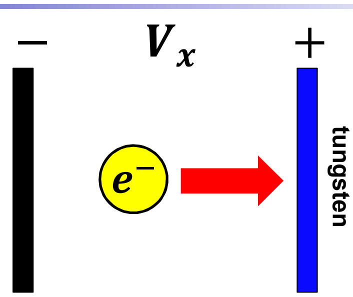
$$\Delta x = -\frac{\ln(0.8)}{2 \times 11.3} = \mathbf{0.01}\ \text{cm}$$

Example 5



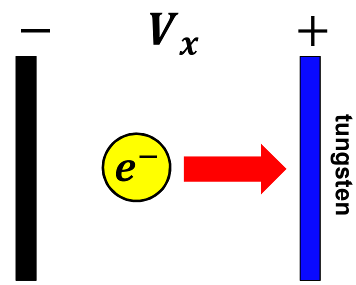
One electron moves across $V_x = 120$ kV and hits many tungsten atoms. Given that the binding energy of the tungsten is $E_B = 4$ keV, how many atoms can be ionized by the electron **at most**?

Example 5



Energy of electron: $E_e = e^- \times V_x = 120$ keV

Example 5



Energy of electron: $E_e = e^- \times V_x = 120$ keV

Number of atoms ionized: $n = E_e/E_B = 30$