UCONN
UNIVERSITY OF CONNECTICUT

# Introduction to Medical Imaging Part II

ENGR 1166 Biomedical Engineering

## 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

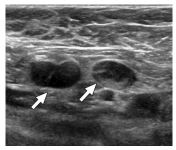
- It is used because
  - ***It does not require radiation exposure***
  - ***It is non-invasive and safe***
  - ***It is fast and (relatively) inexpensive***

## Ultrasound imaging

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

fetus monitoring

heart monitoring

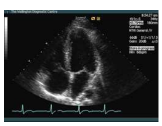


detection of malignant breast tumors

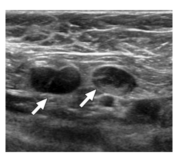
## Ultrasound imaging

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

fetus monitoring

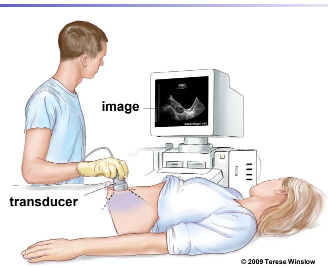


heart monitoring



detection of malignant breast tumors

## A typical ultrasound setup



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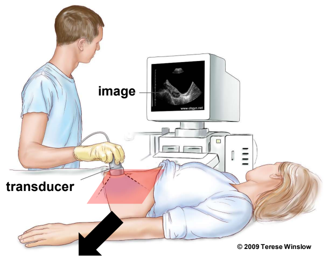
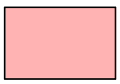
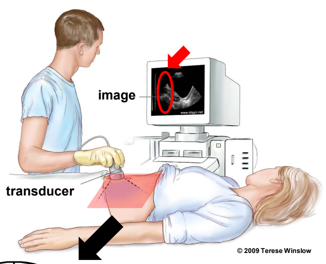
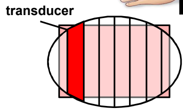


1) Consider the scanned skin surface as a 2-D plane: for every point covered by the transducer, an image of the tissue underneath is recreated on screen

## A typical ultrasound setup

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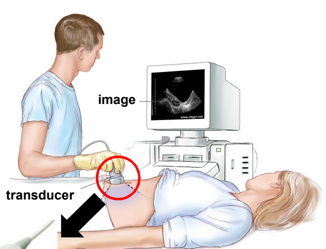
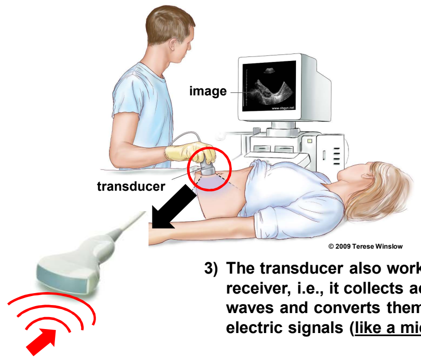



2) The transducer is a device that converts electrical signals into acoustic waves (<u>like a speaker</u>)

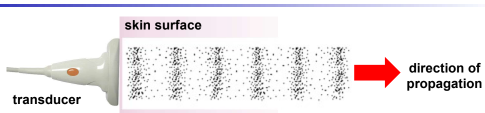
## A typical ultrasound setup




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

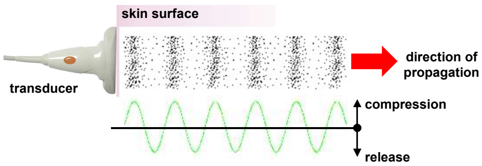
## Ultrasound waves


## Ultrasound waves



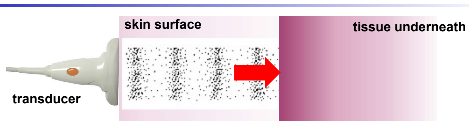

- Ultrasound waves propagate through the skin by compressing and releasing small volumes of tissue

## Ultrasound waves



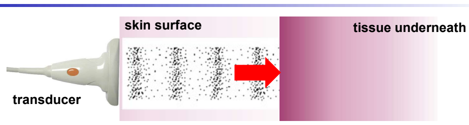

- Ultrasound waves propagate through the skin by compressing and releasing small volumes of tissue
- Molecules in the tissue move back and forth in the same direction the wave is traveling

## Ultrasound waves



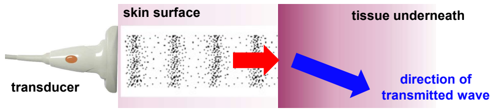

- Let us suppose that the wave hits another layer of tissue (e.g., muscle, bone, or fat, etc.)

## Ultrasound waves



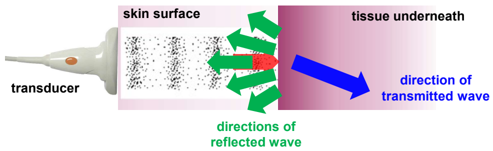

- Let us suppose that the wave hits another layer of tissue (e.g., muscle, bone, or fat, etc.)
- The density of matter varies with the tissue and it is different from the superficial skin layer

## Ultrasound waves: echo



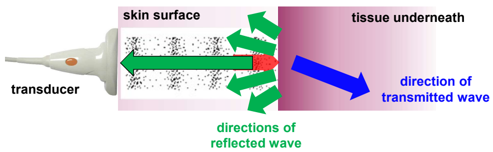

- As a result, the wave will propagate in the new tissue but with lower amplitude (less intensity) and a different direction (**refraction**)

## Ultrasound waves: echo



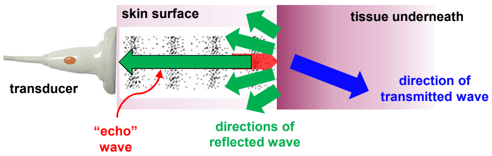

- As a result, the wave will propagate in the new tissue but with lower amplitude (less intensity) and a different direction (**refraction**)
- The wave will be in part reflected (**scattering**), i.e., a wave will propagate backward within the original tissue along **multiple directions**

## Ultrasound waves: echo



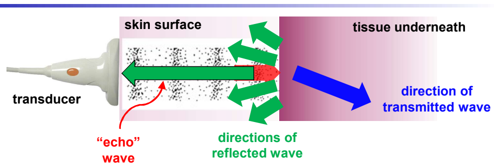

- At least one of the reflected waves will hit back the transducer (a phenomenon called **"echo"**)

## 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




- Two aspects characterize the echo wave:
  - **Delay** (since the emission of the source wave from the transmitter)
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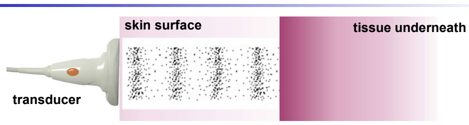
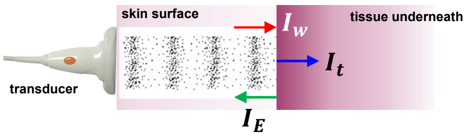
***The image depends on both***

## Intensity of the echo wave



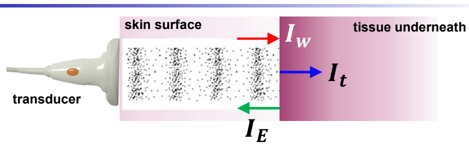

- The **intensity** of the echo wave depends on the two tissues that form the interface

## 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

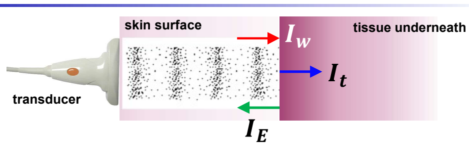
## Intensity of the echo wave




- 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

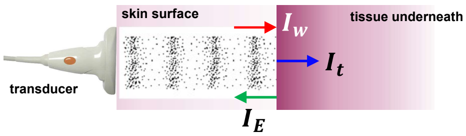



- It can be shown that:

reflection coefficient

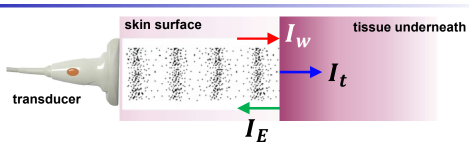
$$I_E = R \times I_w$$
$$I_t = (1 - R) \times I_w$$
$$0 < R < 1$$

## 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**)

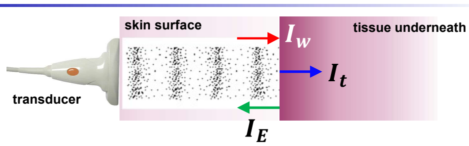
## Acoustic impedance




- ❑ 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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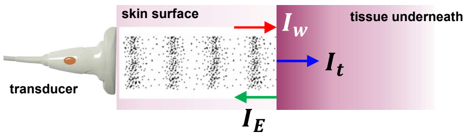
tissue density

## Acoustic impedance

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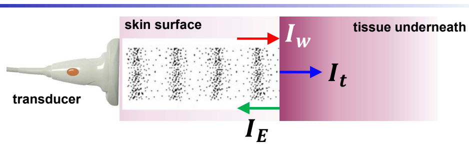
velocity of the wave in the tissue

$$Z = v \times \rho$$

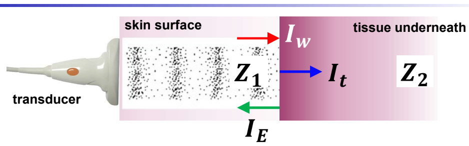
## Acoustic impedance




- ❑ Impedance $Z$ is measured in "Rayl":

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

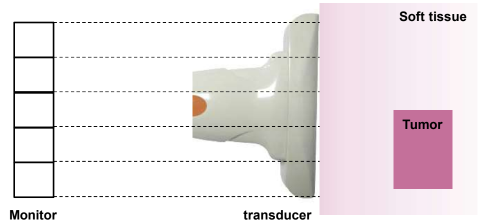
## Acoustic impedance




- ❑ The reflection coefficient $R$ is:

$$R = \left(\frac{Z_2 - Z_1}{Z_1 + Z_2}\right)^2$$

## An intuition of how the system works

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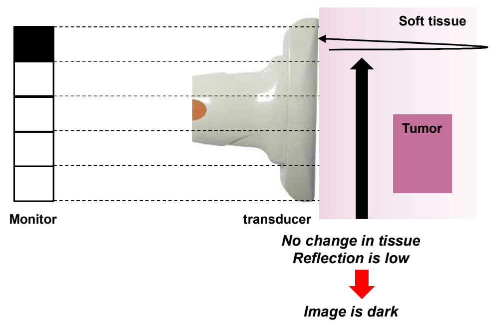


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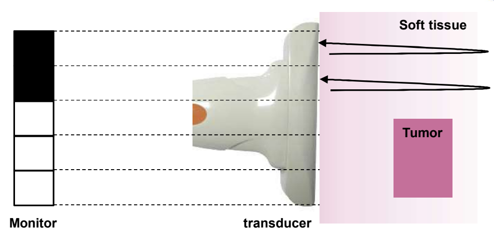

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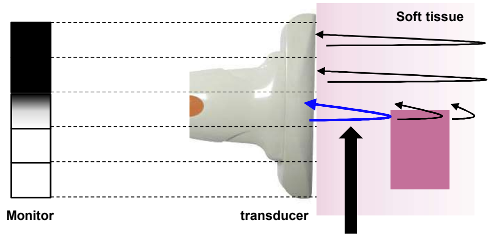
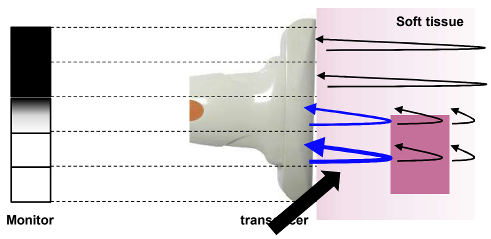



*We are at the border of the tumor mass*
*Reflection is higher (R is closer to 1)*
*Delay for the echo wave is shorter*

*Image becomes brighter*

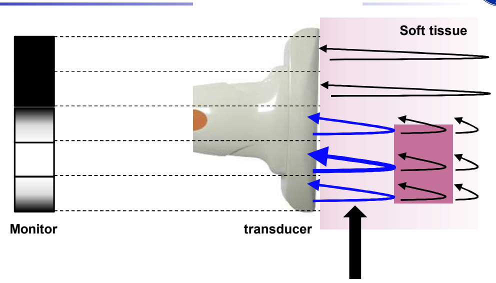
## An intuition of how the system works




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

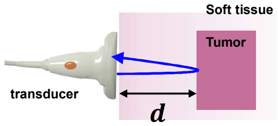
*Image becomes very bright*

## An intuition of how the system works




*We are now onto the other*
*border of the tumor mass*

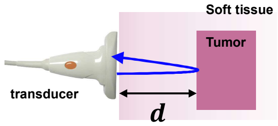
## Example 1




- 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?

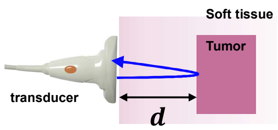
## Example 1




- 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) |
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| Lung | 0.18 |
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$$R = 0.01 = \left(\frac{Z_{tumor} - Z_{fat}}{Z_{fat} + Z_{tumor}}\right)^2 \Rightarrow Z_{tumor} = \frac{1.1}{0.9} Z_{fat} = 1.64 \times 10^6 \text{Rayl}$$

## Radiography

- It exploits **electromagnetic waves** (**X-rays**, wavelength: [0.1,1] nm*, frequency: $3 \times 10^{16}$ Hz to $3 \times 10^{19}$ 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

## Radiography

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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

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

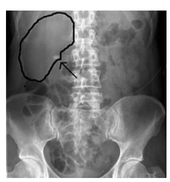
## Applications of radiography

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

lungs

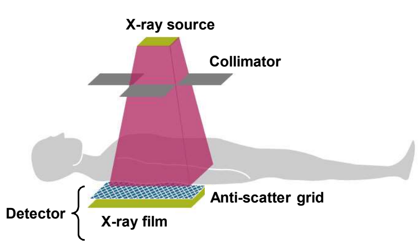
bones

teeth



kidney

## A typical radiography setup



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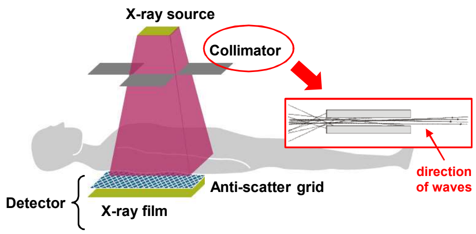
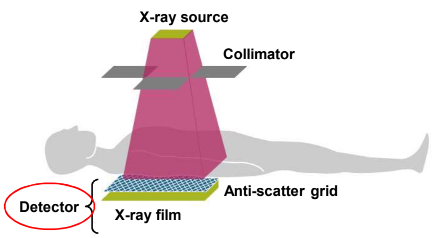


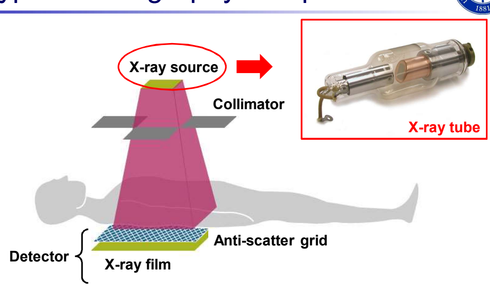

*The collimator makes the directions of the waves more aligned in a specific direction*

## 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

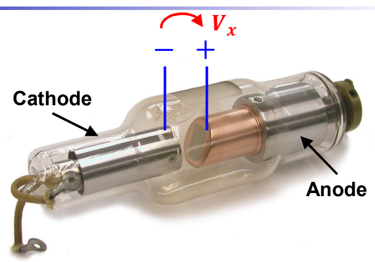



*The source consists of an **X-ray tube**, which generates X-rays by releasing electrons against a plate made of tungsten*

## X-ray tube

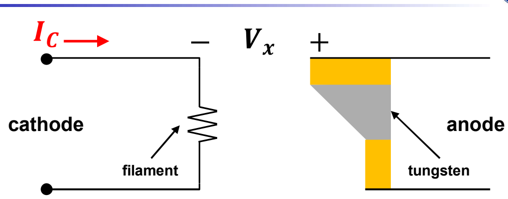
The X-ray tube uses electric currents and voltages to generate X-rays

## X-ray tube



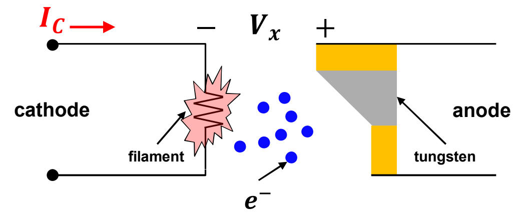

First, a high voltage difference ($V_x$~30-150 kV) is applied between anode and cathode across an empty junction

## 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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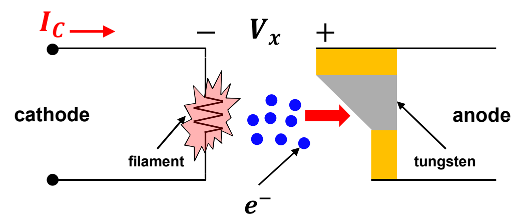
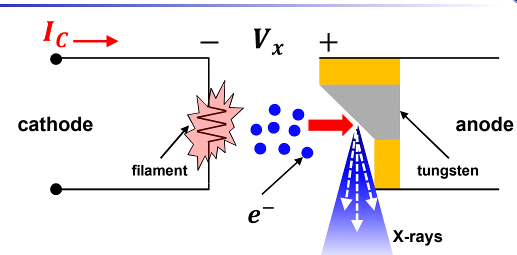


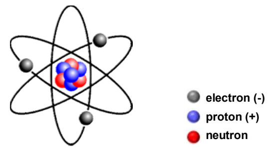

Third, because of the high voltage $V_x$, electrons are steered toward the tungsten plate on the anode

## X-ray tube



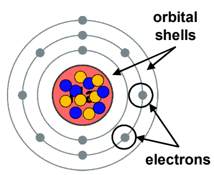

When hit by the electrons, the tungsten atoms emit X-rays with an angle that facilitates the propagation outside the tube

## Emission of X-rays: background



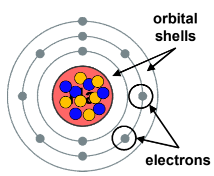

- An electron is an atomic particle with **negative charge** ($e^{-} \cong -1.6 \times 10^{-19}$ C)
- Electrons move around the nucleus along orbital shells

## Emission of X-rays: background



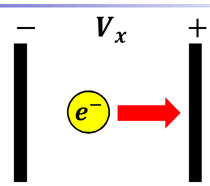

- An orbital shell can host only a **finite** number of electrons
- Electrons fill in the orbital shells **closest** to the nucleus first

## Emission of X-rays: background



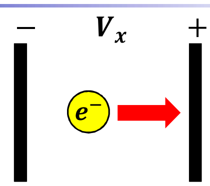

- The **closer** the shell to the nucleus, the **lower** the energy of the shell's electrons
- An electron has the **highest energy** when it is **not bounded** to any orbital shell (it is free to move away)

## 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

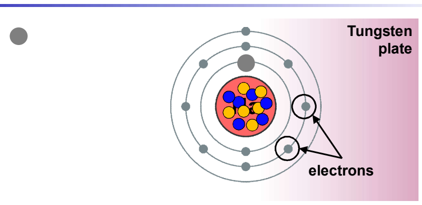
## Emission of X-rays: background




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

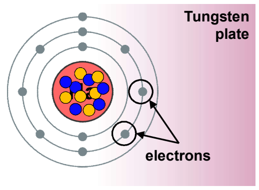
$$1\ \text{eV} \overset{\text{def}}{=} 1\ e^- \times 1\ \text{V} \cong 1.6 \times 10^{-19}\ \text{J}$$

## 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

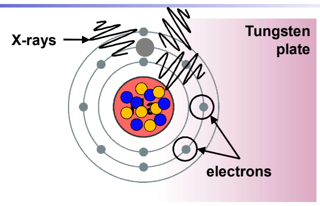
## Emission of X-rays




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

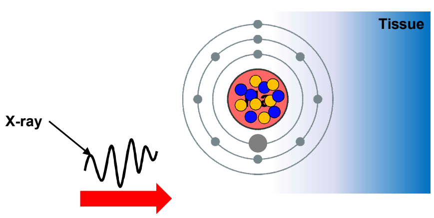
- Hydrogen = 13.6 eV
- Air: 29 eV
- Lead: 1 KeV
- **Tungsten: 4 KeV**

## Emission of X-rays



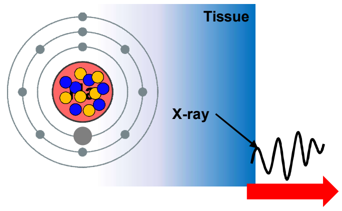

Another electron from an outer orbital shell moves to the inner shell to fill in the vacancy and – doing so – it releases energy in the form of X-rays

## Propagation of X-rays



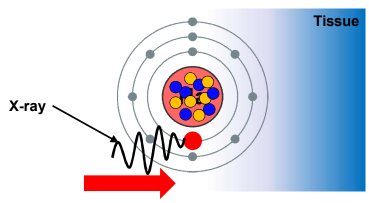

Now let us assume that a beam of X-rays has left the X-ray tube and reaches a target tissue (e.g., bones, lungs, etc.)

## Propagation of X-rays



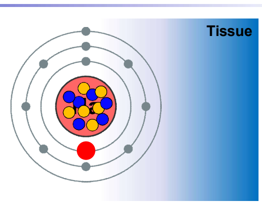

**Option 1:** The X-ray does not interact with atoms and manages to propagate through the tissue and to reach the other side

## Propagation of X-rays



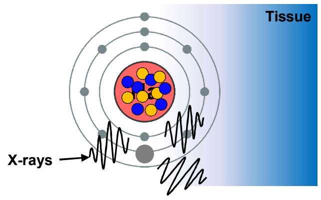

**Option 2:** The X-ray hits an atom. The X-ray will be absorbed and its energy will be transferred to the electron in the inner shell

## Propagation of X-rays



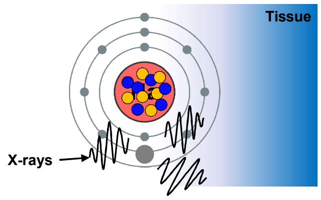

As a result, the electron receiving energy will move away from the atom (**ionization**) …

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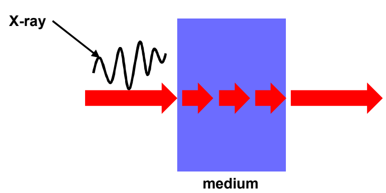
*That's why bones are so clearly identifiable in an X-ray image*

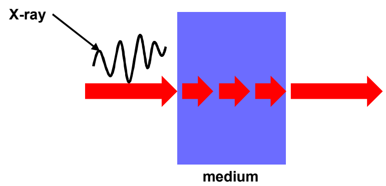
## X-ray attenuation

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



## X-ray attenuation

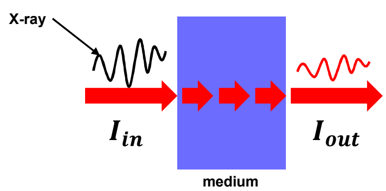
- Let us assume that a medium (e.g., tissue) let the X-rays pass through
- The medium will oppose to the passage of the wave




## X-ray attenuation

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

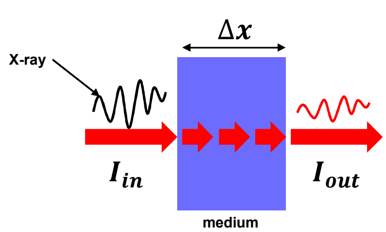
$$I_{out} = R \times I_{in}$$
$$0 < R < 1$$




## X-ray attenuation

- The attenuation depends on the thickness of the medium

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



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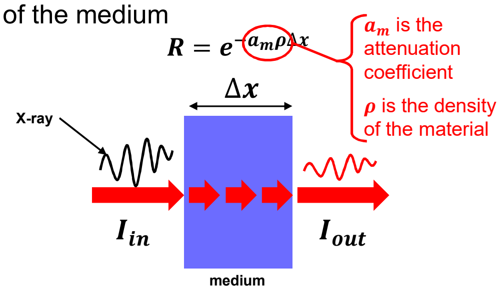


## Example 3

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

How much is $I_{out}$?

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

⬇

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

## Example 4

How much should $\Delta x$ be to obtain $R$ =0.8?

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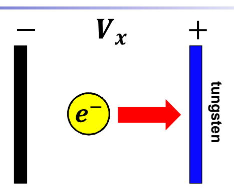
$$R = e^{-a_m \rho \Delta x}$$

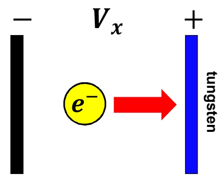
$$\Delta x = -\frac{\ln(0.8)}{2\times 11.3} = \mathbf{0.01} \text{ cm}$$

## Example 5



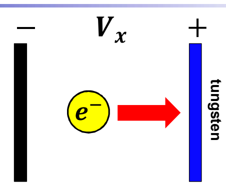

One electron moves across $V_x$ = 120 kV and hits many tungsten atoms. Given that the binding energy of the tungsten is $E_B$ = 4 keV, how many atoms can be ionized by the electron **at most**?

## 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: $n = E_e/E_B = 30$