PHY1203: General Physics III

Chapter 38
Photons: Light Waves Behaving as Particles

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- No tutorial in Week 1. Total ~6 tutorials.

Schedule of the course (tentative)

Week	Date	Content
7	02-Mar	Chap. 38 Photons
8	09-Mar	
9	16-Mar	Chap. 39 Matter Wave
10	23-Mar	
Homework Assignment 3		
11	30-Mar	Chap. 40 Quantum Mechanics
12	06-Apr	
13	13-Apr	Review
Final Exam		

Schedule of the tutorials (tentative)

Week	Date	
1	12-Jan	No tutorial
2	19-Jan	Tutorial 1
3	26-Jan	No tutorial
4	9-Feb	Tutorial 2
5	16-Feb	No tutorial
6	23-Feb	Tutorial 3
7	2-Mar	No tutorial
8	9-Mar	Tutorial 4
9	16-Mar	No tutorial
10	23-Mar	Tutorial 5
11	30-Mar	No tutorial
12	06-Apr	Tutorial 6
13	13-Apr	No tutorial

If it ain't broke, don't fix it

MAY 1977

ing tough, hard-driving, and dedicated to sound management and fiscal integrity.

Mr. Lance is confident that, as the thrust and character of the Carter administration become better defined, whatever uncertainty and skepticism about the administration are harbored by American businessmen will gradually fall aside.

"The President is very cautious about spending," Mr. Lance told *Nation's Business*. "He does not like to spend any more money than is necessary. What he does fiscally will always be done on the side of good management."

Bert Lance is determined to strengthen the M part of OMB.

"We have to be concerned about management practices in government," he says. "I can't understand business enterprise.

After four years in state government, Mr. Lance developed a taste for politics. He ran for the Democratic nomination for governor in 1974, but finished third in the primary. The reputation he earned in state government served him well otherwise, however. The National Bank of Georgia, in Atlanta, tapped him for its presidency.

He was not long on the job when he decided to wrest the bank from its out-of-state owner, Financial General Bancshares, of Washington, D. C. He prevailed on a group of Georgia investors to buy a controlling interest. Bert Lance borrowed money from Manufacturers Hanover Trust and picked up a big slice of the stock for himself.

In two years, under the Lance leadership, National Bank of Georgia government is more present in the minds of Americans than it ever has been," he says. "This is an idea whose time has come. The President is experienced in reorganization. He's willing to spend the time to accomplish it. Unless you're totally committed, it's awfully easy to get comfortable in the bureaucracy. The President is totally committed. He won't tolerate inefficiency."

Saving billions

Bert Lance believes he can save Uncle Sam billions if he can get the government to adopt a simple motto: "If it ain't broke, don't fix it."

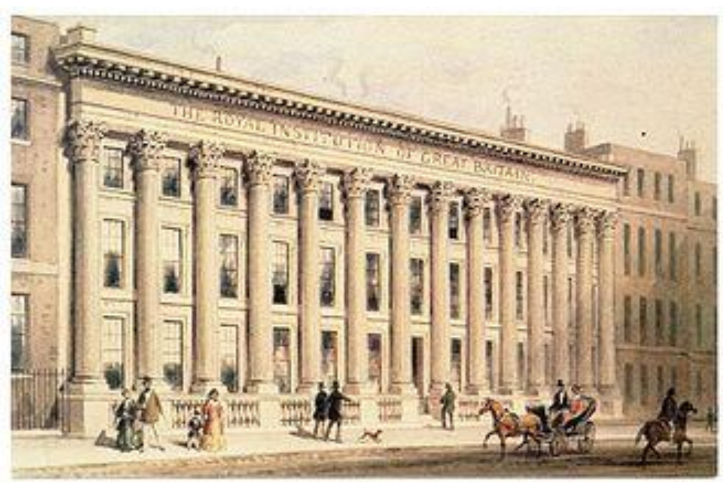
He explains:

"That's the trouble with government: Fixing things that aren't broken and not fixing things that are broken." □

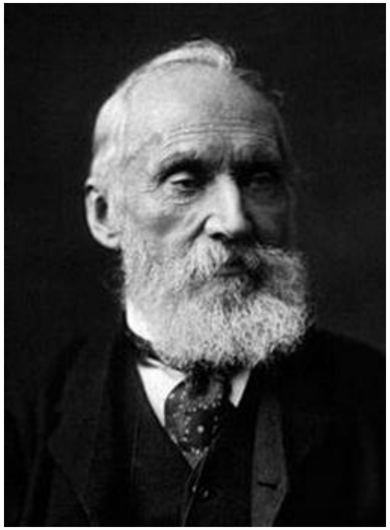
Lord Kelvin’s speech in RI

- On Friday, April 27, 1900, the British physicist Lord Kelvin gave a speech entitled “*Nineteenth-Century Clouds over the Dynamical Theory of Heat and Light*”, which began:

> ***The beauty and clearness of the dynamical theory, which asserts heat and light to be modes of motion, is at present obscured by two clouds.***



The Royal Institution of Great Britain, London, ca. 1838



William Thomson, 1st Baron Kelvin (1824-1907)

Lord Kelvin’s speech in RI

- Kelvin then explained that the "clouds" were two unexplained phenomena, which are the final couple of holes that needed to be filled in before having a complete understanding of the universe.
- The two clouds are
  - The inability to detect the luminous ether, specifically the failure of the Michelson-Morley experiment
  - The black body radiation effect known as the *ultraviolet catastrophe*
- Many contemporary physicists then strongly believed the main role of physics in that day was to just measure known quantities to a great degree of precision, out to many decimal places of accuracy.
- But … is that the case?

References by Other Physicists

- Kelvin's speech has since been referenced many many times, for one reason: he was wrong.

> ***William Thomson (Lord Kelvin), an influential British physicist, famously proclaimed that physics was over, except for two small clouds on the horizon. These "clouds" turned out to be the clues that led us to quantum theory and relativity theory.***
>
> —Lee Smolin, *The Trouble with Physics*

References by Other Physicists

In 1900, Kelvin himself did note that "two clouds" were hovering on the horizon, one to do with properties of light's motion and the other with aspects of the radiation objects emit when heated, but there was a general feeling that these were mere details, which, no doubt, would soon be addressed.

Within a decade, everything changed. As anticipated, the two problems Kelvin had raised were promptly addressed, but they proved anything but minor. Each ignited a revolution, and each requires a fundamental rewriting of nature's laws.

—Brian Greene, *The Fabric of the Cosmos*

Dawn of Modern Physics

- At around 1900 in Europe and the U.S., some scientists started to realize that the classical physics *is* broken.

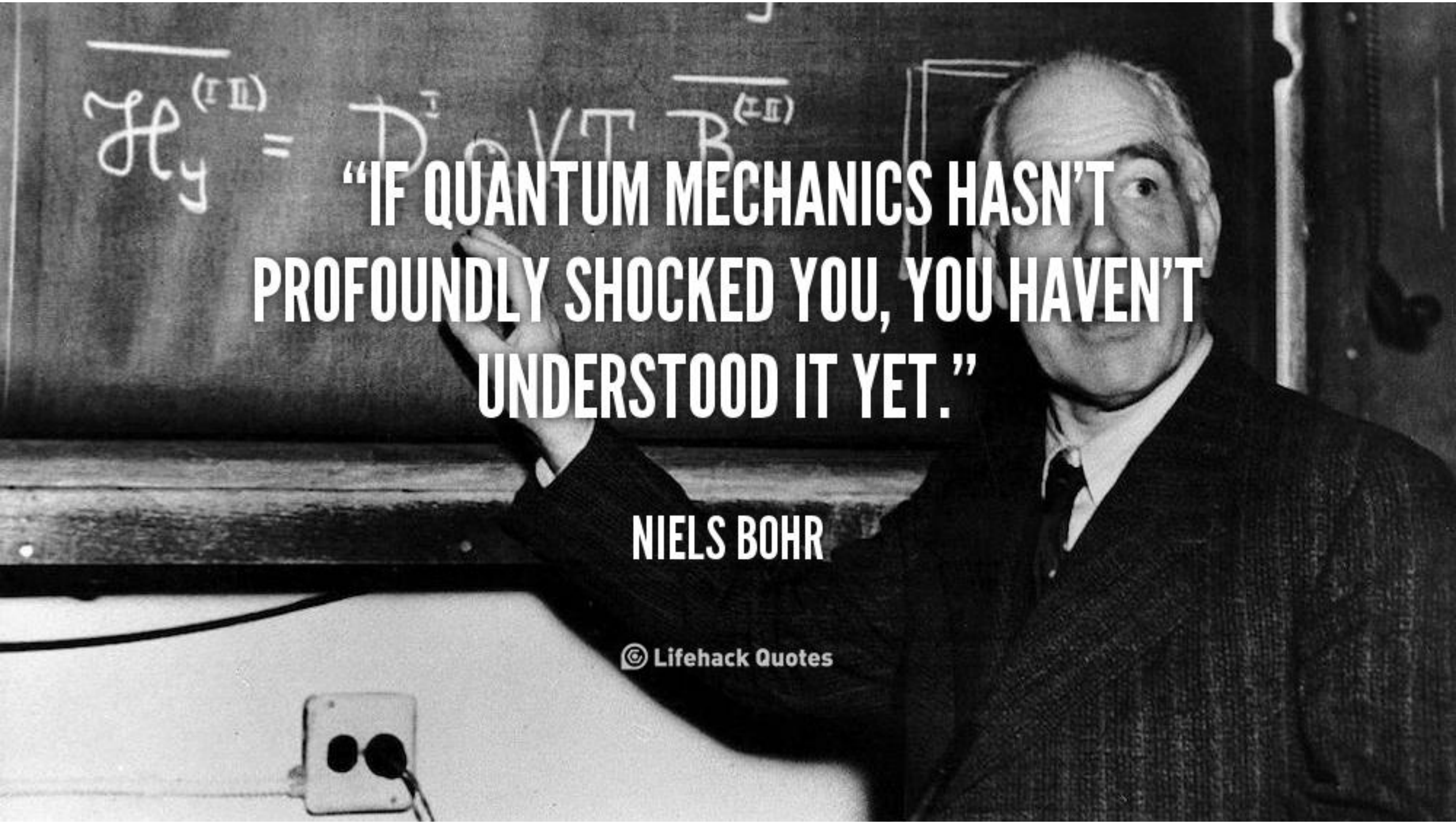
- Development of technologies has led to a much wider range of experimental observations. However, the classical physics is unable or insufficient to explain them.

- The first cloud mentioned by Kelvin, the inability to detect ether, leads to relativity (recent discovery of the gravitational wave is also part of the prediction from relativity) (not covered in this course)

- The second cloud, the ultraviolet catastrophe, leads to quantum mechanics, which we will study in the following weeks.

Dawn of Modern Physics

- The difficulties of the classical physics we are going to study in the next few lectures include:
  - Photoelectric effect
  - Structure of an atom/atomic spectra
  - The blackbody radiation and the ultraviolet catastrophe
- We are also going to study the revolutionary ideas that gave birth to modern physics:
  - Photon
  - Matter wave
  - Quanta
  - Uncertainty principle
- We shall also meet many physicists along the way.


"IF QUANTUM MECHANICS HASN'T PROFOUNDLY SHOCKED YOU, YOU HAVEN'T UNDERSTOOD IT YET."
NIELS BOHR
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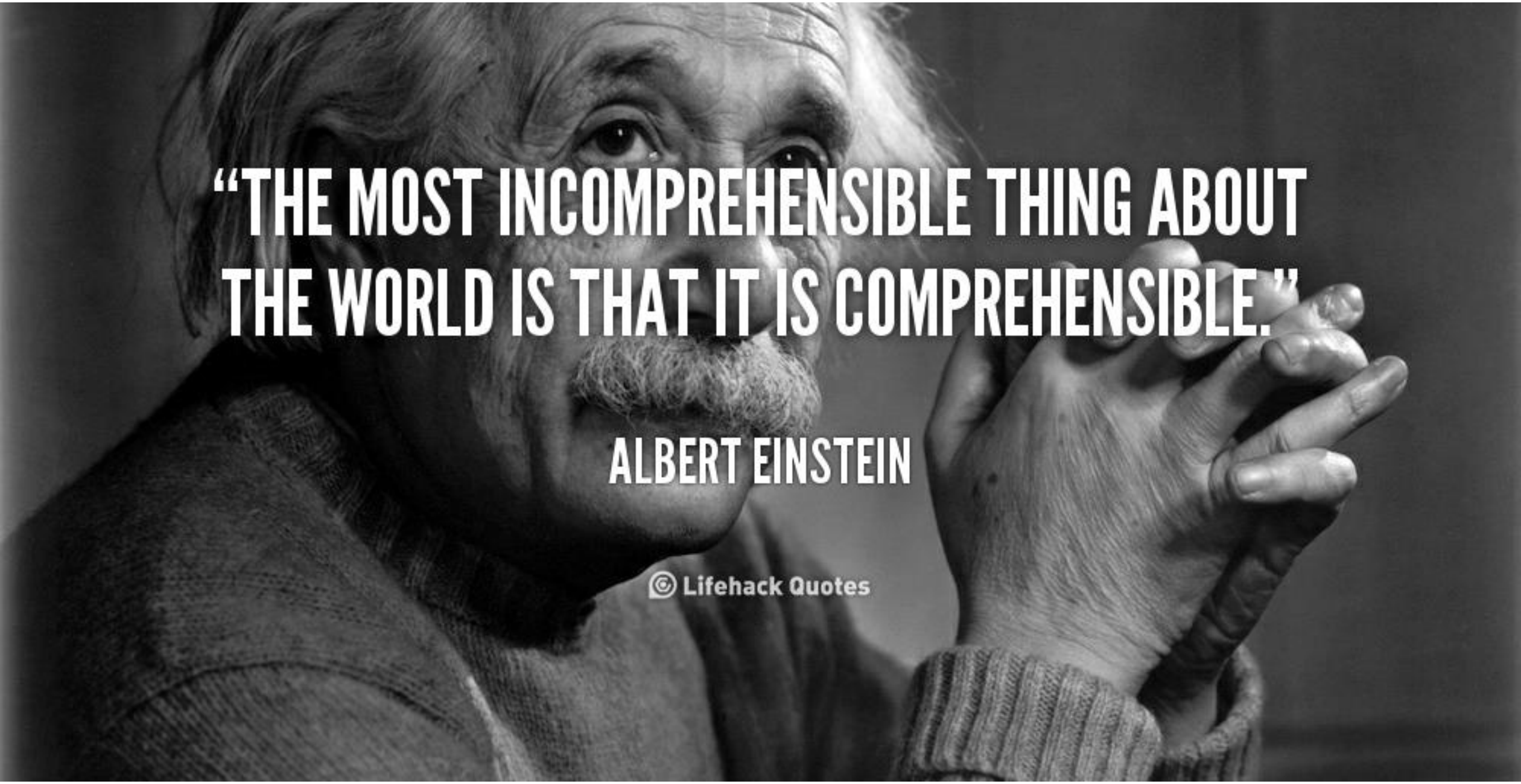
"THE MOST INCOMPREHENSIBLE THING ABOUT THE WORLD IS THAT IT IS COMPREHENSIBLE."
ALBERT EINSTEIN
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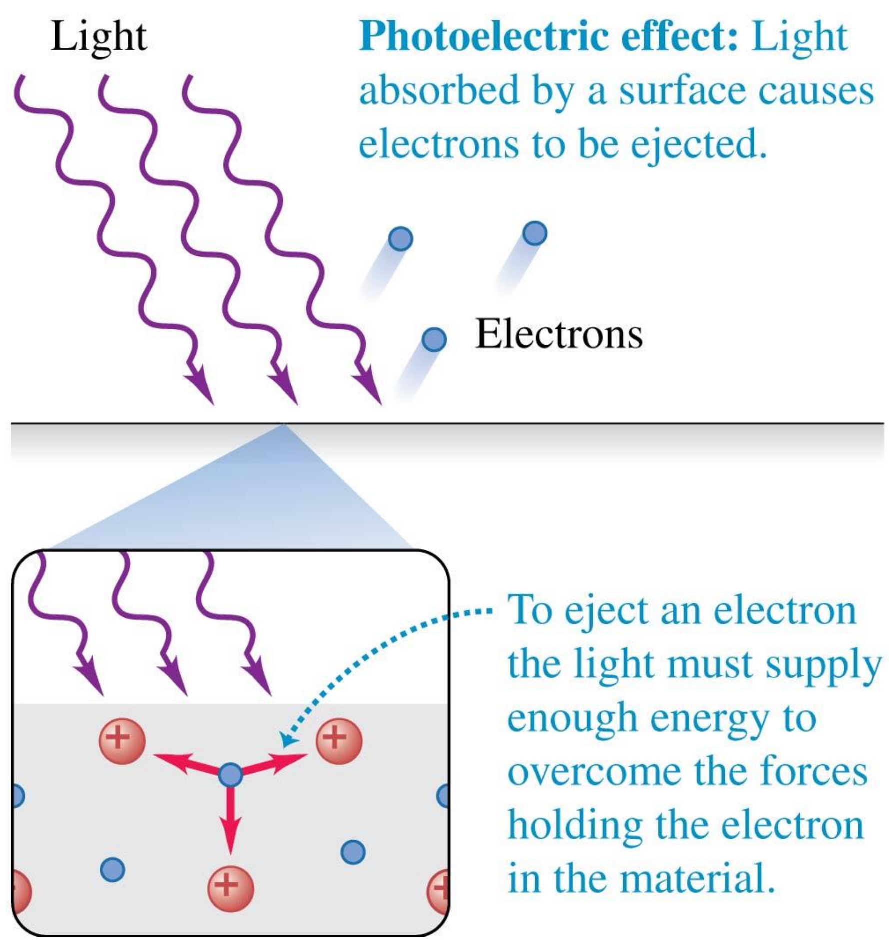
Outline for this lecture

Looking forward at …

- what the photoelectric effect is
- how Einstein's photon picture of light explains the photoelectric effect.
- how experiments with x-ray production provided evidence that light is emitted in the form of photons.
- how the scattering of gamma rays helped confirm the photon picture of light.
- how the Heisenberg uncertainty principle imposes fundamental limits on what can be measured.

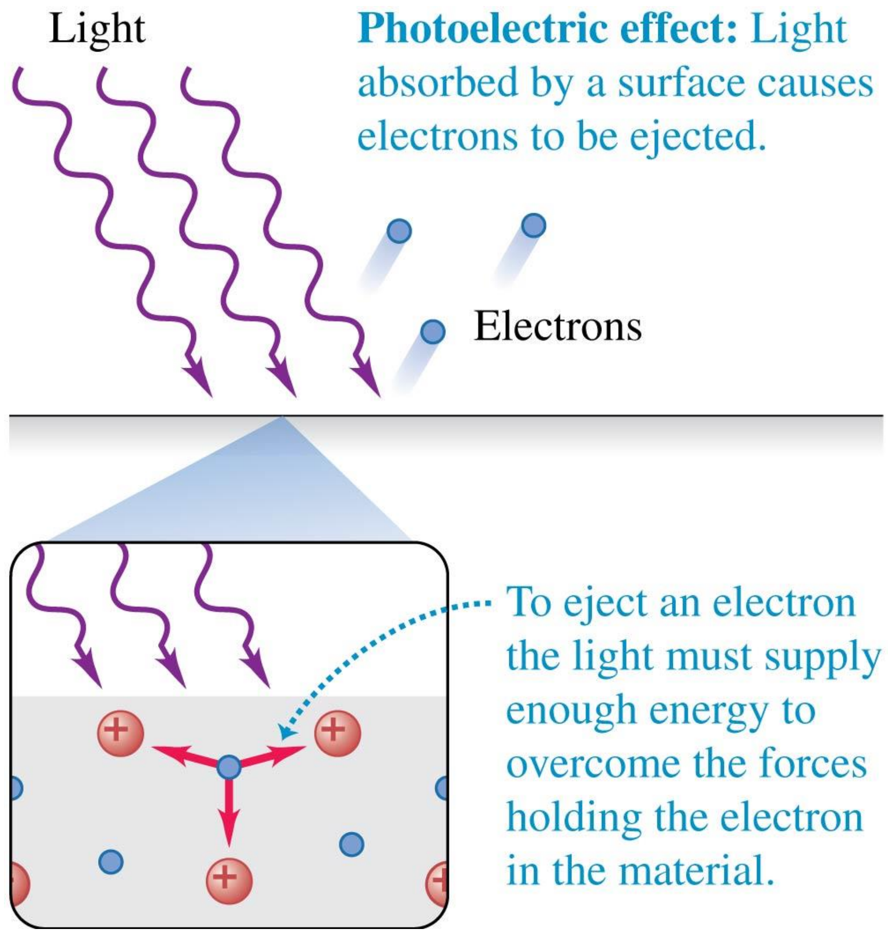
The photoelectric effect

- Between 1877 and 1905, scientists have observed that many metals emit electrons when light shines upon them.
- The energy in the light is converted into the kinetic energy of electrons.
- The phenomenon is called the **photoelectric effect**.



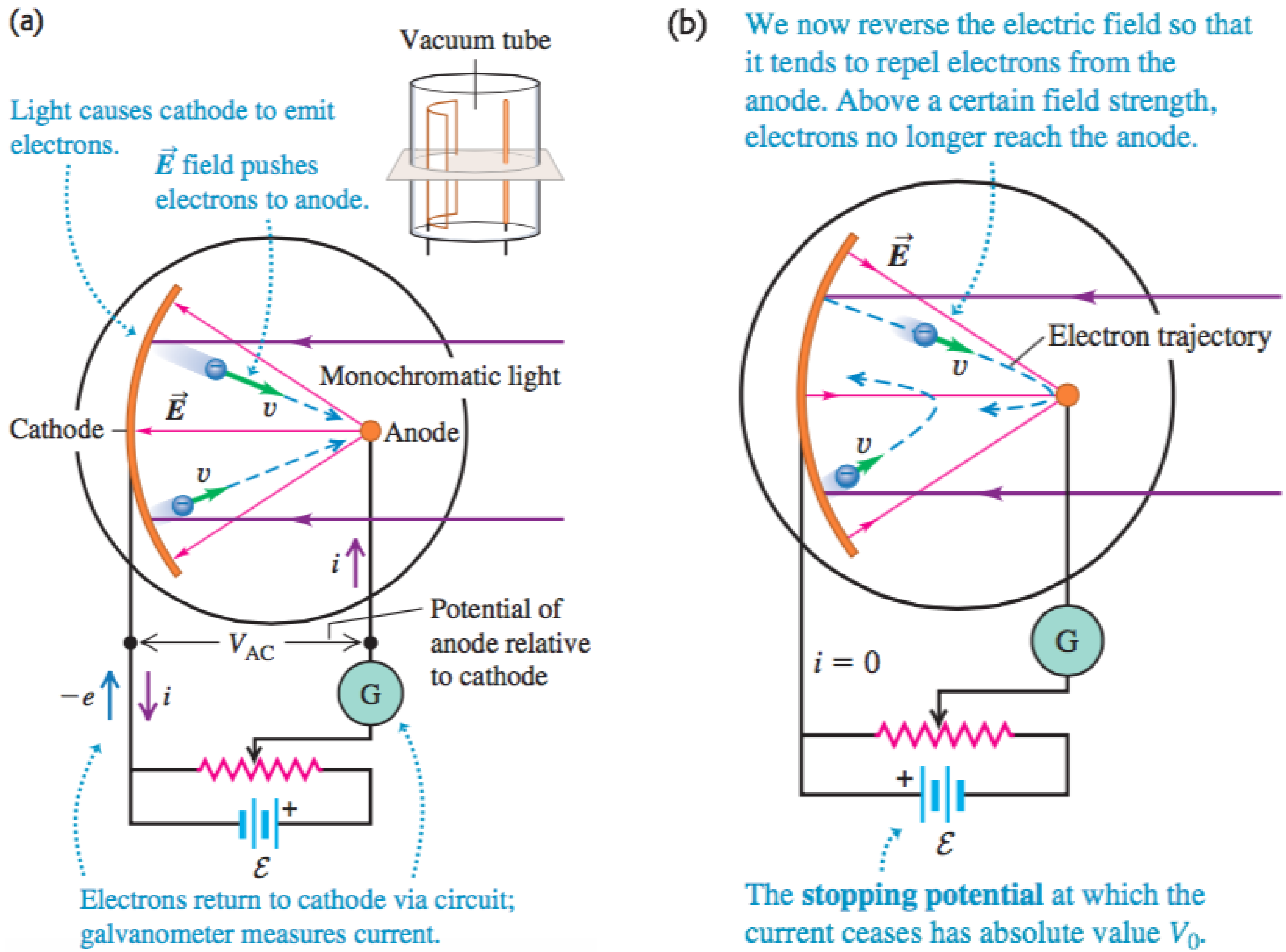
The photoelectric effect

- To escape from the surface, an electron must absorb enough energy from the incident light to overcome the attraction of positive ions in the material.
- These attractions constitute a potential-energy barrier; the light supplies the "kick" that enables the electron to escape.



- The minimum amount of energy to eject a single electron from a particular surface is called the **Work Function.**
- The ejected electrons ("photoelectrons") form the **photocurrent**.

Stopping potential



Stopping Potential

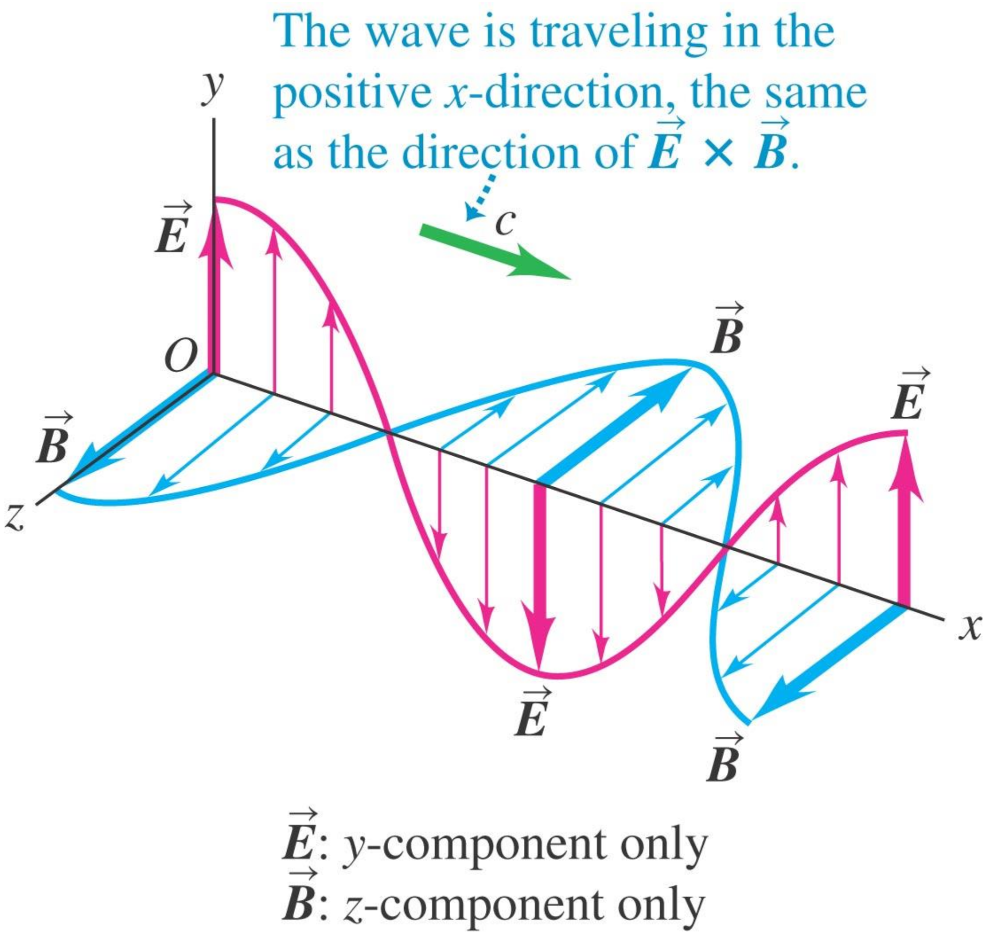
- We can determine the maximum kinetic energy K_{max} of the emitted electrons by making the potential of the anode relative to the cathode, V_{AC}, just negative enough so that the current stops.
- This occurs for $V_{AC} = -V_0$, where V_0 is called the stopping potential.
- As an electron moves from the cathode to the anode, the potential decreases by V_0 and negative work $-eV_0$ is done on the (negatively charged) electron. The work–energy theorem gives

$$W_{tot} = -eV_0 = \Delta K = 0 - K_{max}$$
$$K_{max} = \tfrac{1}{2} m v_{max}^{2} = eV_0$$

(maximum kinetic energy of photoelectrons)

- Hence by measuring the stopping potential V_0, we can determine the maximum kinetic energy with which electrons leave the cathode.
- How do we expect the photocurrent to depend on the voltage across the electrodes and on the frequency and intensity of the light?

Light as electromagnetic waves



The energy stored in the light is proportional to its amplitude squared. (recall for periodic motion, $E = kA^2/2$, and E does not depend on ω)

Prediction from Classical Electromagnetism

1. The photoelectric effect should occur for light of any frequency, and the magnitude of the photocurrent **should not depend on the frequency** of the light.

2. If the light falling on the surface is very faint, some time may elapse before the total energy absorbed by the surface equals the work function. We expect **a time delay** between when we switch on the light and when photoelectrons appear.

3. Because the energy delivered to the cathode surface depends on the intensity of illumination, we expect the stopping potential to increase with increasing **light intensity**. Since intensity does not depend on frequency, we further expect that the stopping potential **should not depend on the frequency** of the light.

Actual experimental results

1. **The photocurrent depends on the light frequency**. For a given material, monochromatic light with a frequency below a minimum threshold frequency produces no photocurrent, regardless of intensity.

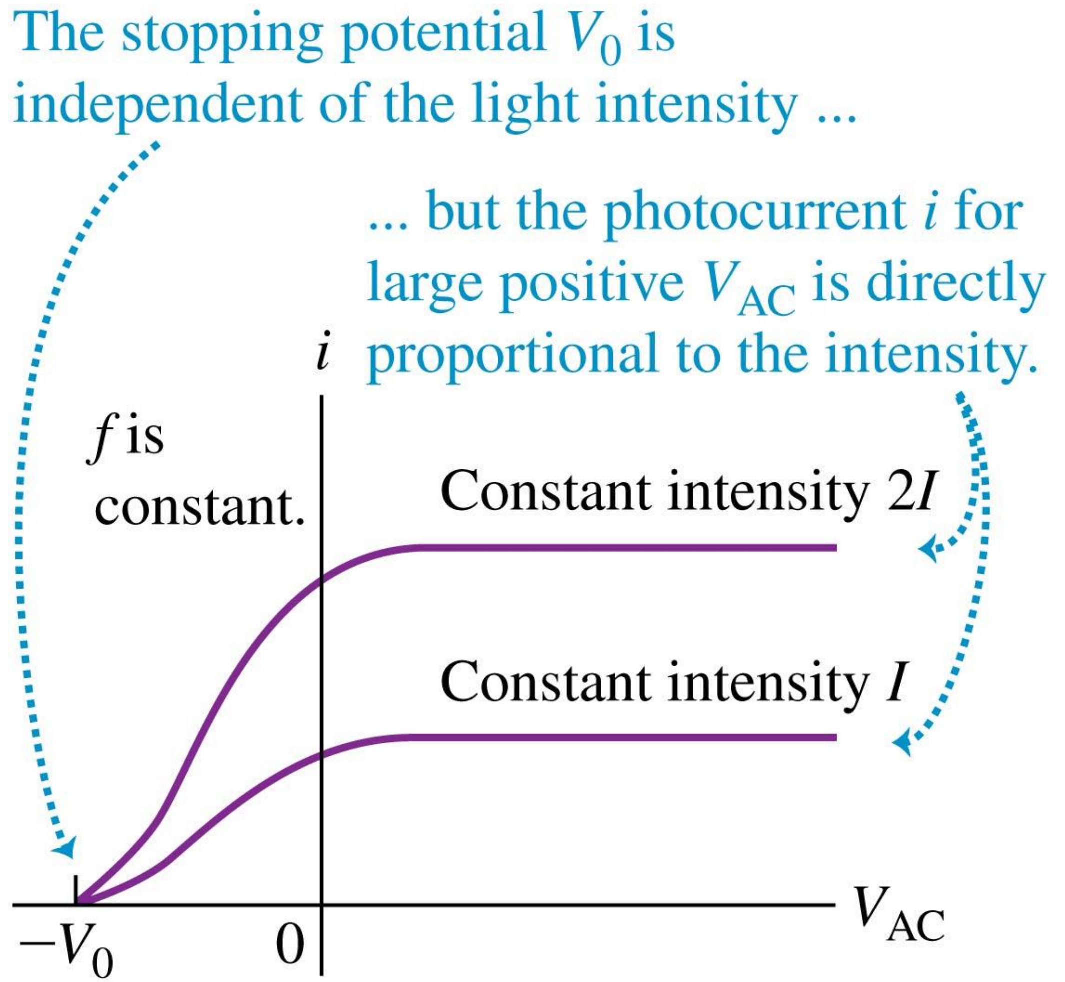
2. **There is no measurable time delay between when the light is turned on and when the cathode emits photoelectrons** (assuming the frequency of the light exceeds the threshold frequency). This is true no matter how faint the light is.

3. **The stopping potential does not depend on intensity, but does depend on frequency**. The only effect of increasing the intensity is to increase the number of electrons per second and hence the photocurrent *i*. The greater the light frequency, the higher the energy of the ejected photoelectrons.

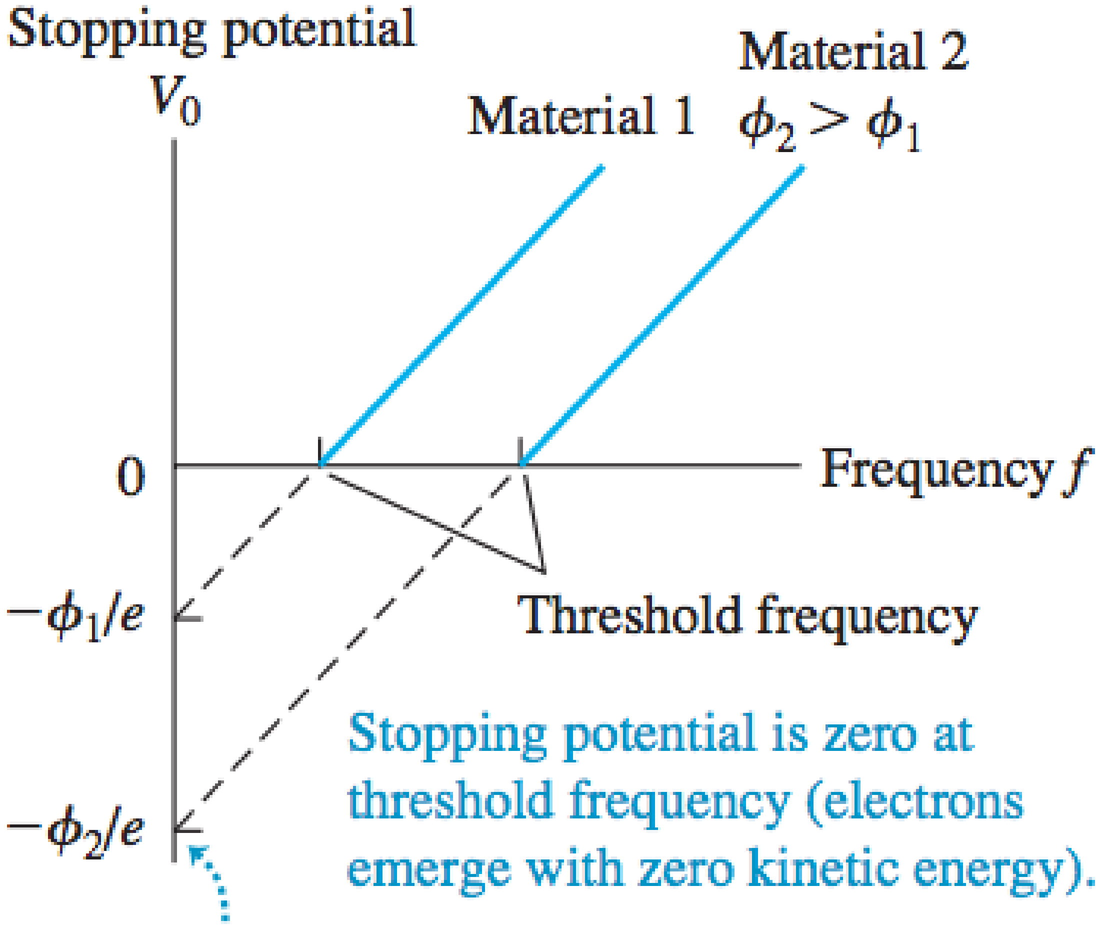
Photocurrent in the photoelectric effect

- Shown are graphs of photocurrent as a function of potential difference V_{AC} for light of a given frequency and two different intensities.

- The reverse potential difference $-V_0$ needed to reduce the current to zero is the same for both intensities.



Threshold frequency



Contradictions

Classical E&M:

- Photocurrent **independent** of frequency
- Time delay between turning on the light and seeing photoelectrons
- Stopping potential depends on the **intensity but not frequency**

Actual:

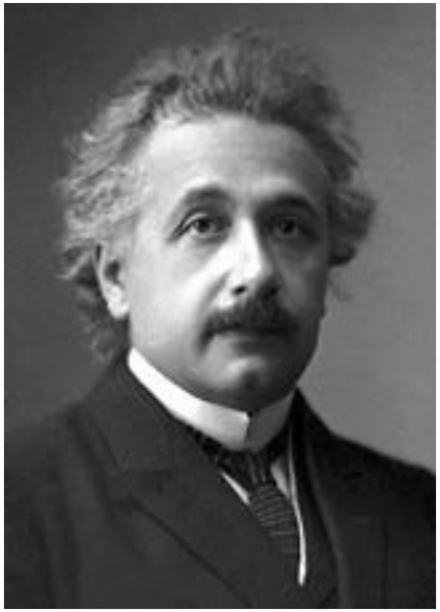
- Photocurrent **dependent** of frequency
- **NO** Time delay between turning on the light and seeing photoelectrons
- Stopping potential depends on the **frequency but not intensity**

Thoughts

- Lights as E&M waves does carry energy proportional to amplitude squared.
- The energy in the light has been converted into the kinetic energy of electrons.
- But probably such energy conversion occurs in a different way than what we thought before?
- Can light manifest itself as something other than E&M wave, whose energy is only dependent on frequency but not the amplitude?
- This means that we need to set aside the "wave nature" of the light for the moment.

Einstein's photon explanation

- In 1905, Einstein made the radical postulate that a beam of light consists of small packages of energy called **photons** or quanta.
- This postulate was an extension of an idea developed five years earlier by Max Planck to explain the properties of blackbody radiation (ultraviolet catastrophe), which we will mention later.



Albert Einstein (1879-1955)

Nobel Prize in Physics 1921

"for his services to Theoretical Physics, and **especially for his discovery of the law of the photoelectric effect**".

Einstein’s photon explanation

- A beam of light consists of small packages of energy called **photons** or quanta.
- The energy of an individual photon is:

$$\underset{\text{Energy of a photon}}{E} = \overset{\text{Planck's constant}}{h}\,\underset{\text{Frequency}}{f} = \frac{h\,\overset{\text{Speed of light in vacuum}}{c}}{\underset{\text{Wavelength}}{\lambda}}$$

- Here **Planck’s constant** is
  $h = 6.626 \times 10^{-34}\ \text{J} \cdot \text{s} = 4.136 \times 10^{-15}\ \text{eV} \cdot \text{s}$
- An individual photon arriving at a surface is absorbed by a single electron.
- The electron can escape from the surface only if the energy it acquires is greater than the work function ϕ.

Solutions to the contradictions

Actual observations:

- Photocurrent **dependent** of frequency
- **NO** Time delay between turning on the light and seeing photoelectrons
- Stopping potential depends on the **frequency but not intensity**

Solutions:

- If frequency low, photon energy not enough to excite photocurrent; photons with larger frequencies will generate larger currents
- The energy is transmitted from the photon to the electron instantaneously, regardless of the intensity
- K_{max} depends on the energy got from the photon, dependent only on frequency but not intensity

Einstein's explanation of the photoelectric effect

- This explains how the energy of an emitted electron in the photoelectric effect depends on the frequency of light used.
- The greater the work function of a particular material, the higher the minimum frequency needed to emit photoelectrons.

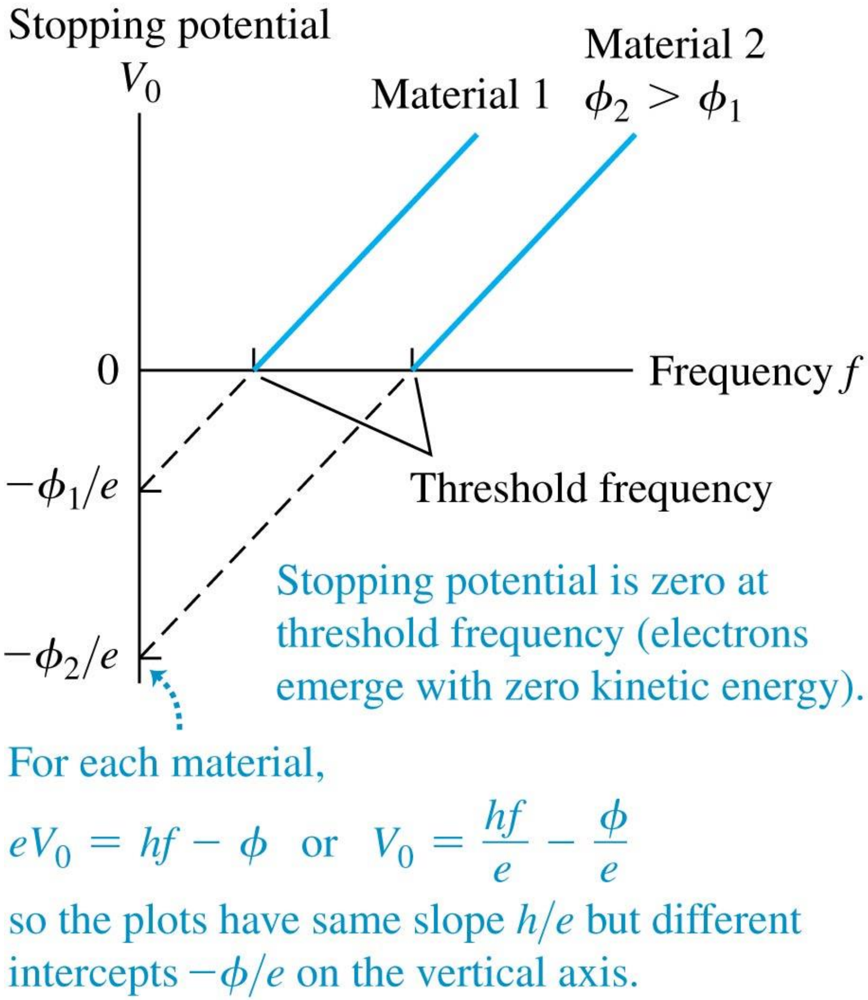


Table 38.1: Work functions of several elements

Element	Work Function (eV)
Aluminum	4.3
Carbon	5.0
Copper	4.7
Gold	5.1
Nickel	5.1
Silicon	4.8
Silver	4.3
Sodium	2.7

Photoelectric effect: Things to remember

$$K_{\mathrm{max}} = \frac{1}{2}mv_{\mathrm{max}}{}^2 = hf - \phi$$

$$K_{\mathrm{max}} = eV_0$$

$$eV_0 = hf - \phi \qquad \text{(photoelectric effect)}$$

Q38.1

In an experiment to demonstrate the photoelectric effect, you shine a beam of monochromatic blue light on a metal plate. As a result, electrons are emitted by the plate. Complete the sentence: "If you increase the intensity of the light but keep the color of the light the same, the number of electrons emitted per second will __________ and the maximum kinetic energy of the emitted electrons will __________."

A. increase, increase

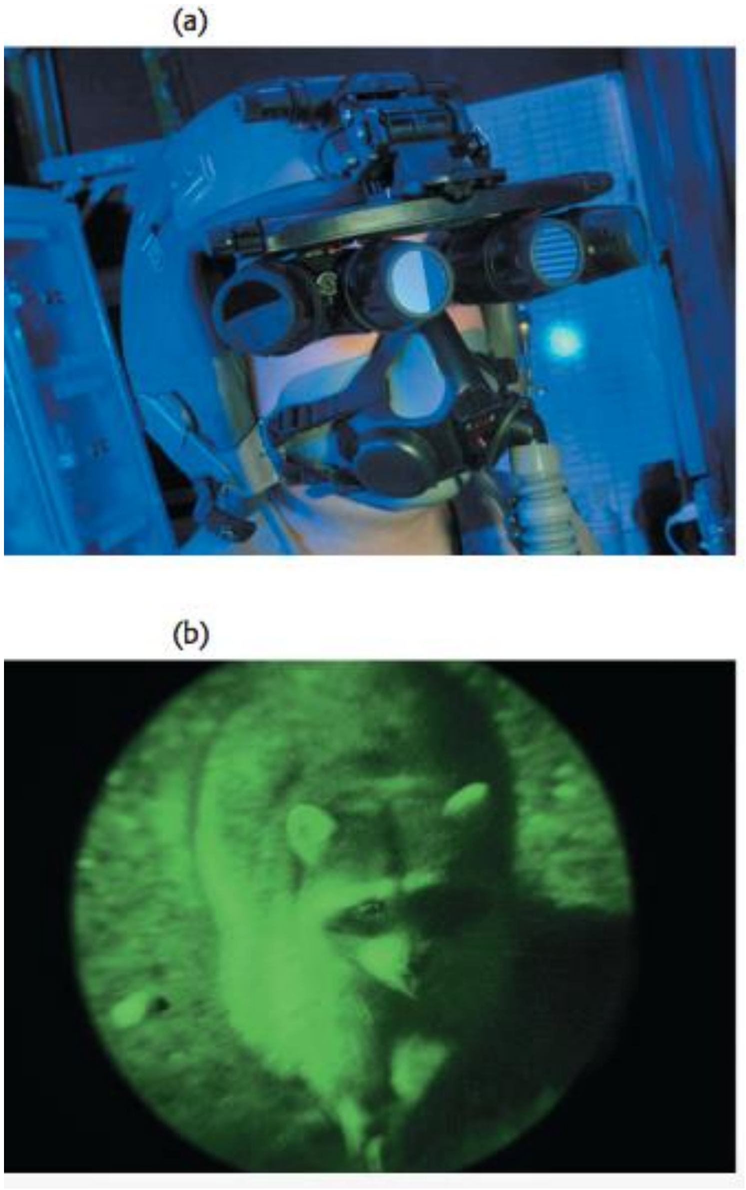
✔ B. increase, stay the same

C. stay the same, increase

D. stay the same, stay the same

E. none of the above

Application of the photoelectric effect



38.2 (a) A night-vision scope makes use of the photoelectric effect. Photons entering the scope strike a plate, ejecting electrons that pass through a thin disk in which there are millions of tiny channels. The current through each channel is amplified electronically and then directed toward a screen that glows when hit by electrons. (b) The image formed on the screen, which is a combination of these millions of glowing spots, is thousands of times brighter than the naked-eye view.

Photons are not usual "particles"

CAUTION **Photons are not "particles" in the usual sense** It's common to envision photons as miniature billiard balls or pellets. While that's a convenient mental picture, it's not very accurate. For one thing, billiard balls and bullets have a rest mass and travel slower than the speed of light c, while photons travel at the speed of light and have *zero* rest mass. For another thing, photons have wave aspects (frequency and wavelength) that are easy to observe. The fact is that the photon concept is a very strange one, and the true nature of photons is difficult to visualize in a simple way. We'll discuss the dual personality of photons in more detail in Section 38.4.

Example 38.2: A photoelectric-effect experiment

While conducting a photoelectric-effect experiment with light of a certain frequency, you find that a reverse potential difference of 1.25 V is required to reduce the current to zero. Find (a) the maximum kinetic energy and (b) the maximum speed of the emitted photoelectrons.

EXECUTE: (a) From Eq. (38.1),

$$K_{\text{max}} = eV_0 = (1.60 \times 10^{-19}\ \text{C})(1.25\ \text{V}) = 2.00 \times 10^{-19}\ \text{J}$$

(Recall that $1\ \text{V} = 1\ \text{J/C}$.) In terms of electron volts,

$$K_{\text{max}} = eV_0 = e(1.25\ \text{V}) = 1.25\ \text{eV}$$

since the electron volt (eV) is the magnitude of the electron charge e times one volt (1 V).

(b) From $K_{\text{max}} = \frac{1}{2}mv_{\text{max}}{}^2$ we get

$$v_{\text{max}} = \sqrt{\frac{2K_{\text{max}}}{m}} = \sqrt{\frac{2(2.00 \times 10^{-19}\ \text{J})}{9.11 \times 10^{-31}\ \text{kg}}}$$

$$= 6.63 \times 10^5\ \text{m/s}$$

Example 38.3: Determining ϕ and h experimentally

For a particular cathode material in a photoelectric-effect experiment, you measure stopping potentials $V_0 = 1.0$ V for light of wavelength $\lambda = 600$ nm, 2.0 V for 400 nm, and 3.0 V for 300 nm. Determine the work function ϕ for this material and the implied value of Planck's constant h.

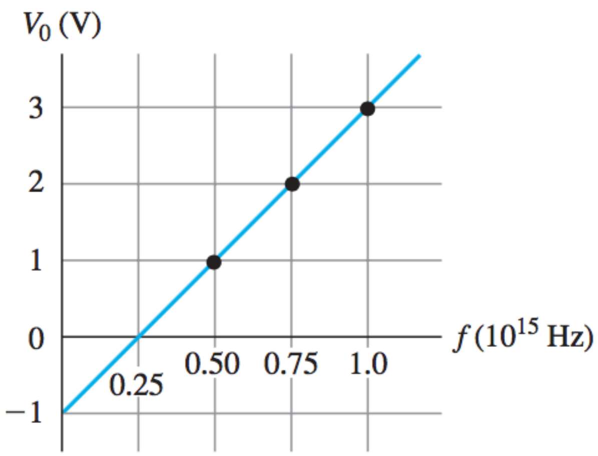
EXECUTE: We rewrite Eq. (38.4) as

$$V_0 = \frac{h}{e}f - \frac{\phi}{e}$$

In this form we see that the slope of the line is h/e and the vertical-axis intercept (corresponding to $f = 0$) is $-\phi/e$. The frequencies, obtained from $f = c/\lambda$ and $c = 3.00 \times 10^8$ m/s, are 0.50×10^{15} Hz, 0.75×10^{15} Hz, and 1.0×10^{15} Hz, respectively. From a graph of these data (see Fig. 38.6), we find

$$-\frac{\phi}{e} = \text{vertical intercept} = -1.0 \text{ V}$$

$$\phi = 1.0 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$



and

$$\text{Slope} = \frac{\Delta V_0}{\Delta f} - \frac{3.0 \text{ V} - (-1.0 \text{ V})}{1.00 \times 10^{15} \text{ s}^{-1} - 0} = 4.0 \times 10^{-15} \text{ J} \cdot \text{s/C}$$

$$h = \text{slope} \times e = (4.0 \times 10^{-15} \text{ J} \cdot \text{s/C})(1.60 \times 10^{-19} \text{ C})$$

$$= 6.4 \times 10^{-34} \text{ J} \cdot \text{s}$$

EVALUATE: The value of Planck's constant h determined from your experiment differs from the accepted value by only about 3%. The small value $\phi = 1.0$ eV tells us that the cathode surface is not composed solely of one of the elements in Table 38.1.

Photon momentum

- Every particle that has energy must have momentum.
- Photons have zero rest mass, and a particle with zero rest mass and energy E has momentum with magnitude p given by $E = pc$
- Thus the magnitude p of the momentum of a photon is:

$$\underset{\text{Momentum of a photon}}{p} = \frac{\overset{\text{Photon energy}}{E}}{\underset{\text{Speed of light in vacuum}}{c}} = \frac{\overset{\text{Planck's constant}}{h}\underset{\text{Frequency}}{f}}{\underset{\text{Speed of light in vacuum}}{c}} = \frac{\overset{\text{Planck's constant}}{h}}{\underset{\text{Wavelength}}{\lambda}}$$

- The direction of the photon's momentum is simply the direction in which the electromagnetic wave is moving.

Example 38.1: Laser-pointer photons

A laser pointer with a power output of 5.00 mW emits red light ($\lambda = 650$ nm). (a) What is the magnitude of the momentum of each photon? (b) How many photons does the laser pointer emit each second?

EXECUTE: (a) We have $\lambda = 650 \text{ nm} = 6.50 \times 10^{-7}$ m, so from Eq. (38.5) the photon momentum is

$$p = \frac{h}{\lambda} = \frac{6.626 \times 10^{-34}\ \text{J} \cdot \text{s}}{6.50 \times 10^{-7}\ \text{m}}$$
$$= 1.02 \times 10^{-27}\ \text{kg} \cdot \text{m/s}$$

(b) From Eq. (38.2), the energy of a single photon is

$$E = pc = (1.02 \times 10^{-27}\ \text{kg} \cdot \text{m/s})(3.00 \times 10^{8}\ \text{m/s})$$
$$= 3.06 \times 10^{-19}\ \text{J} = 1.91\ \text{eV}$$

The laser pointer emits energy at the rate of 5.00×10^{-3} J/s, so it emits photons at the rate of

$$\frac{5.00 \times 10^{-3}\ \text{J/s}}{3.06 \times 10^{-19}\ \text{J/photon}} = 1.63 \times 10^{16}\ \text{photons/s}$$

Example: Photoconductivity

Silicon films become better electrical conductors when illuminated by photons with energies of 1.14 eV or greater, an effect called **photoconductivity**. Which of the following wavelengths of electromagnetic radiation can cause photoconductivity in silicon films? (i) ultraviolet light with λ = 300 nm; (ii) red light with λ = 600 nm; (iii) infrared light with λ = 1200 nm.

Photon energy $$E = \frac{hc}{\lambda}$$

We want to satisfy $$E \geq 1.14\text{eV}$$

Therefore

$$\begin{aligned}\lambda &\leq \frac{hc}{1.14\text{eV}}\\ &= \frac{4.14\times 10^{-15}\text{eV}\cdot\text{s}\cdot 3\times 10^{8}\text{m/s}}{1.14\text{eV}}\\ &= 1088\text{nm}\end{aligned}$$

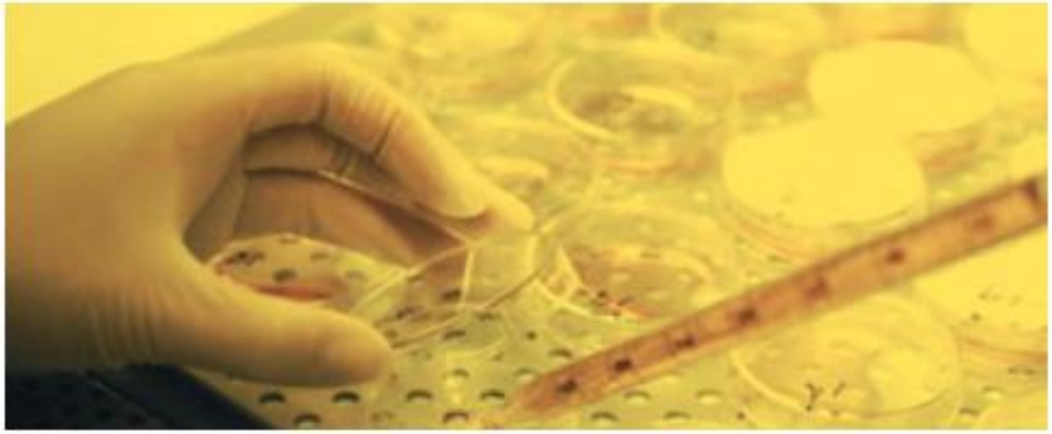
Photons in surgery

- This surgeon is using two light sources: a headlamp that emits a beam of visible light and a handheld laser that emits infrared light.

- The light from both sources is emitted in the form of packets of energy--photons.
- The individual photons in the infrared laser are actually less energetic than the photons in the visible light.

Sterilizing with High-Energy Photons (UV light)

One technique for killing harmful microorganisms is to illuminate them with ultraviolet light with a wavelength shorter than 254 nm. If a photon of such short wavelength strikes a DNA molecule within a microorganism, the energy of the photon is great enough to break the bonds within the molecule. This renders the microorganism unable to grow or reproduce. Such ultraviolet germicidal irradiation is used for medical sanitation, to keep laboratories sterile (as shown here), and to treat both drinking water and wastewater.



Light emitted as photons

- The photon model seems to explain the photoelectric effect pretty well.
- However, to fully testify a theory, we should look at other aspects of experiments.
- Light absorbed as photons: photoelectric effect
- Light emitted as photons: X-ray
- Interaction between photons and other particles (after it is emitted and before it is absorbed): Compton scattering, pair production
- We will study the latter two aspects.

Discovery of X-ray

- On Nov. 8th, 1895, German physicist Wilhelm Röntgen discovered a "mysterious" ray when he was studying the cathode rays.
- He named this ray as "X-ray" (signifying the "unknown"), although many others still referred to these as "Röntgen rays" (and the associated X-ray radiograms as, "Röntgenograms") until today, including in German languages.

Wilhelm C. Röntgen (1845-1923)

Nobel Prize in Physics 1901

"in recognition of the extraordinary services he has rendered by the discovery of **the remarkable rays** subsequently named after him".

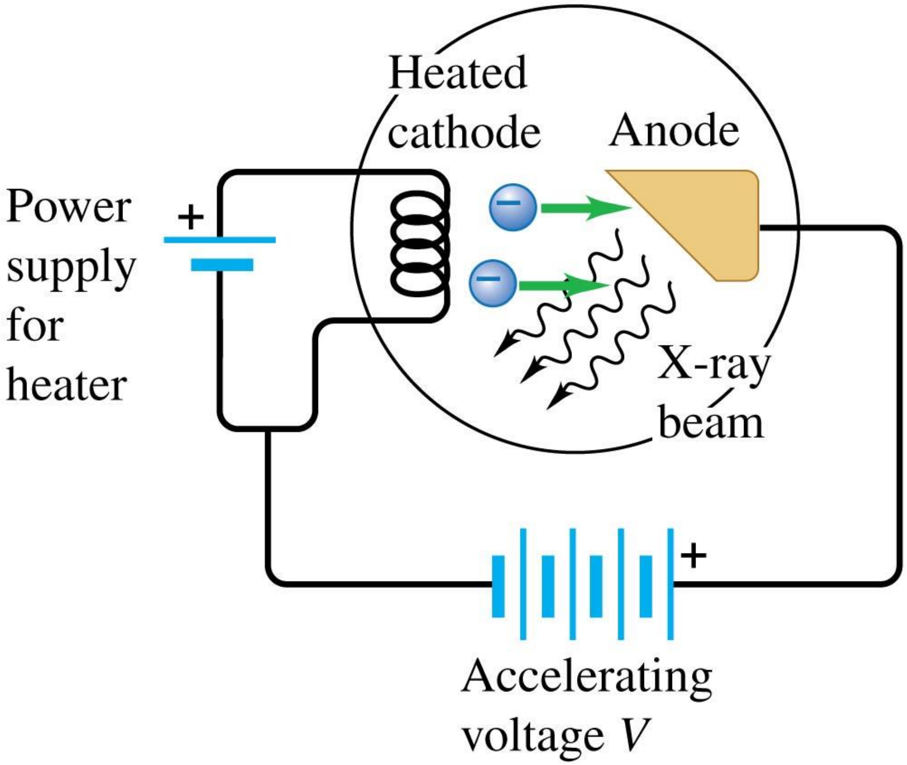
First X-ray radiogram

- Röntgen discovered its medical use when he made a picture of his wife's hand on a photographic plate formed due to X-rays.
- On December 22nd, 1895, he took an x-ray photograph of his wife's hand: Hand mit Ringen (Hand with Rings)
- This was the first photograph of a human body part using X-rays.
- When Röntgen's wife saw the picture, she said "I have seen my death."

Production of X-ray

- Electrons are released from the cathode by thermionic emission, in which the escape energy is supplied by heating the cathode to a very high temperature. (recall the Work function.)
- Electrons are then accelerated toward the anode by a potential difference V_{AC}.
- The bulb is evacuated, so the electrons can travel from the cathode to the anode without colliding with air molecules.
- When V_{AC} is a few thousand volts or more, x rays are emitted from the anode surface.

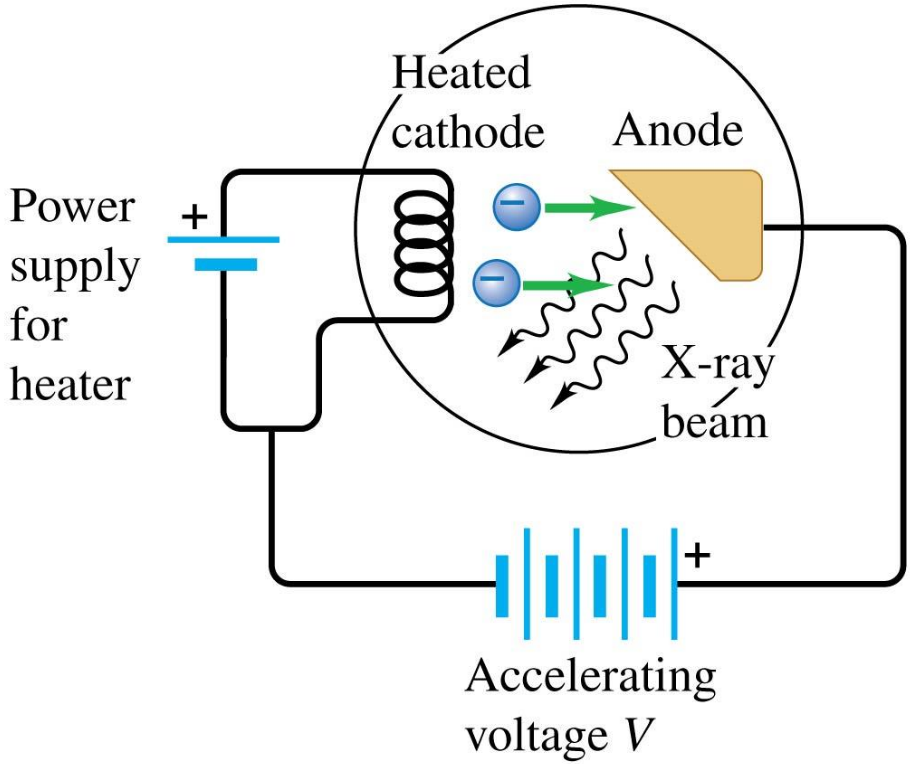
Electrons are emitted thermionically from the heated cathode and are accelerated toward the anode; when they strike it, x rays are produced.



Production of X-ray

- The anode produces X-rays in part by slowing the electrons abruptly
- The process is called Bremsstrahlung ("braking radiation")
- Electrons undergo very large accelerations -> short wavelengths of the x-ray (10^{-9}-10^{-12} m)
- Most electrons are braked by a series of collisions and interactions with anode atoms, so bremsstrahlung produces a continuous spectrum of electromagnetic radiation.

Electrons are emitted thermionically from the heated cathode and are accelerated toward the anode; when they strike it, x rays are produced.



What do we expect from classical E&M?

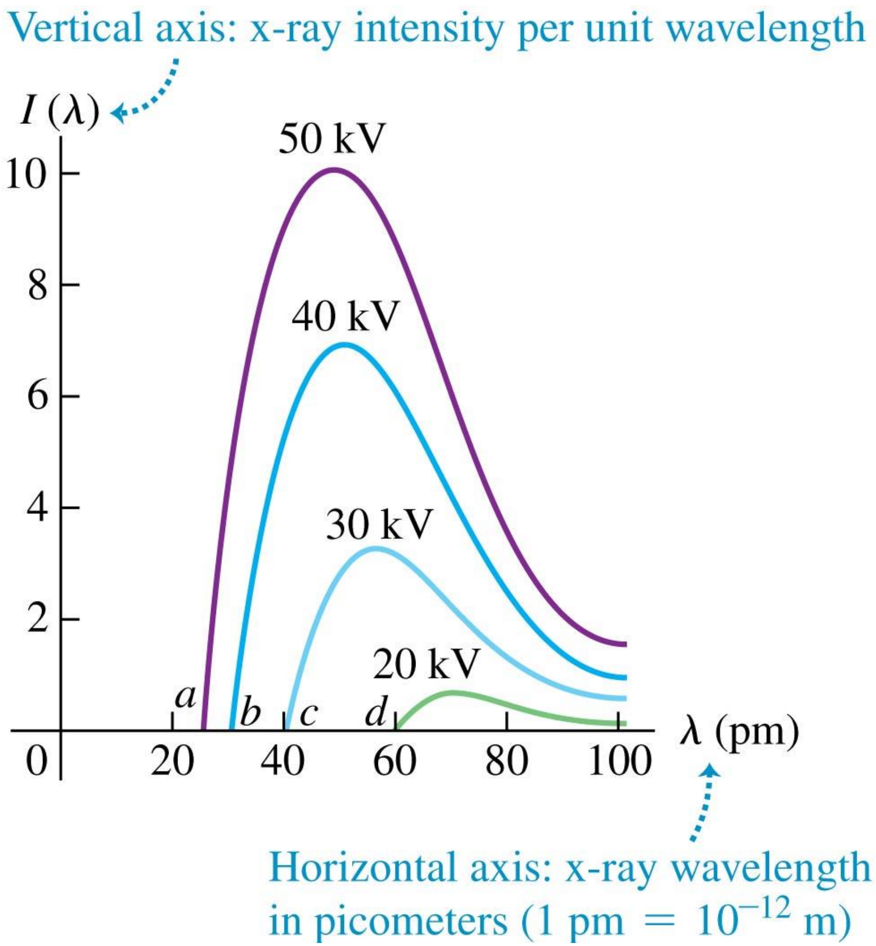
- Prediction from classical E&M:
  The electromagnetic waves produced when an electron slams into the anode should be analogous to the sound waves produced by crashing cymbals together. These waves include sounds of all frequencies. By analogy, the x rays produced by bremsstrahlung should have a spectrum that includes
  all frequencies and hence **all wavelengths**.

Experimental Result

- The Figure shows bremsstrahlung spectra using the same cathode and anode with four different accelerating voltages.

- Not all x-ray frequencies and wavelengths are emitted: Each spectrum has a maximum frequency f_{max} and a corresponding minimum wavelength λ_{min}.

- The greater the potential difference V_{AC}, the higher the maximum frequency and the shorter the minimum wavelength.



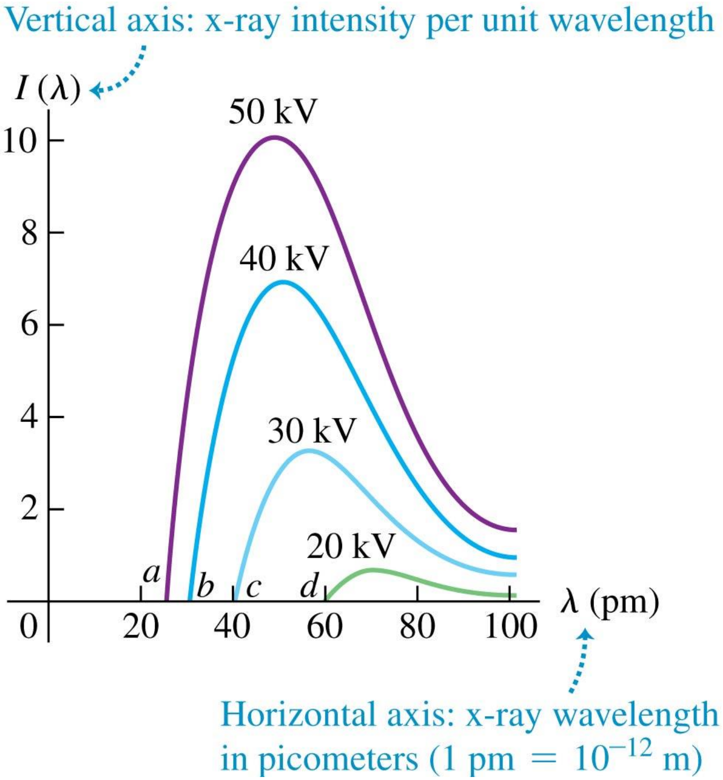
Explanation from the photon model

- Higher-energy electrons can convert their energy into higher-energy photons, which have a shorter wavelength.

$$eV_{AC} = hf_{max} = \frac{hc}{\lambda_{min}} \qquad \text{(bremsstrahlung)}$$

- If only a portion of an electron's kinetic energy goes into producing a photon, the photon energy will be less and the wavelength will be greater than λ_{min}

- The measured λ_{min} agrees with the equation above; it is also material independent as expected from the theory.



So the photon picture is correct!

Q38.3

A beam of electrons is accelerated to high speed and aimed at a metal target. The electrons brake to a halt when they strike the target, and x-ray photons are produced. Complete the sentence: "If you increase the voltage used to accelerate the electrons, the x-ray photon energy will __________ and the x-ray photon wavelength will __________."

A. increase, increase

B. increase, decrease

C. decrease, increase

D. decrease, decrease

E. none of the above

Example 38.4: Producing X-rays

Electrons in an x-ray tube accelerate through a potential difference of 10.0 kV before striking a target. If an electron produces one photon on impact with the target, what is the minimum wavelength of the resulting x rays? Find the answer by expressing energies in both SI units and electron volts.

EXECUTE: From Eq. (38.6), using SI units we have

$$\lambda_{\text{min}} = \frac{hc}{eV_{AC}} = \frac{(6.626 \times 10^{-34}\ \text{J} \cdot \text{s})(3.00 \times 10^{8}\ \text{m/s})}{(1.602 \times 10^{-19}\ \text{C})(10.0 \times 10^{3}\ \text{V})}$$

$$= 1.24 \times 10^{-10}\ \text{m} = 0.124\ \text{nm}$$

Using electron volts, we have

$$\lambda_{\text{min}} = \frac{hc}{eV_{AC}} = \frac{(4.136 \times 10^{-15}\ \text{eV} \cdot \text{s})(3.00 \times 10^{8}\ \text{m/s})}{e(10.0 \times 10^{3}\ \text{V})}$$

$$= 1.24 \times 10^{-10}\ \text{m} = 0.124\ \text{nm}$$

In the second calculation, the "e" for the magnitude of the electron charge cancels the "e" in the unit "eV," because the electron volt (eV) is the magnitude of the electron charge e times one volt (1 V).

X-ray absorption and medical imaging

- Atomic electrons can absorb x rays.
- Hence materials with many electrons per atom tend to be better x-ray absorbers than materials with few electrons.
- Bones contain large amounts of elements such as phosphorus and calcium, with 15 and 20 electrons per atom, respectively.
- In soft tissue, the predominant elements are hydrogen, carbon, and oxygen, with only 1, 6, and 8 electrons per atom, respectively.
- Hence x rays are absorbed by bone but pass relatively easily through soft tissue.

X-ray radiology and Li Hung-chang

- 奧人朗德根新得照相之法：凡衣服、血肉、木石諸質，盡化煙雲；所留存鏡中者，惟五金類及骨殖全副而已。中堂在馬關議約之際，猝遭不知教化人之毒手，槍彈留於面部，至今未出，心頗憂之。此次道出柏靈，知有操朗德根之術者，乃延攝其面影；即見槍子一顆，存於左目之下，纖毫畢現。聞中堂將商之名醫，剖顴出彈。論者曰，名醫雖灼知之，恐未敢遽取之也。

- Chinese politician, Grand Secretariat Li Hung-chang (李鴻章) was shot while negotiating the Treaty of Shimonoseki in 1895, and then while he visited Germany he has taken a x-ray radiology. He was very amazed and named this new technique “照骨術”, the technique of imaging bones. He therefore became the first Chinese who ever took an x-ray exam

X-ray radiology in China

- Dec. 1897, Suzhou (Soochow Hospital 博習醫院) imported the very first X-ray equipment in China “寶鏡新奇”

X-ray radiology in China

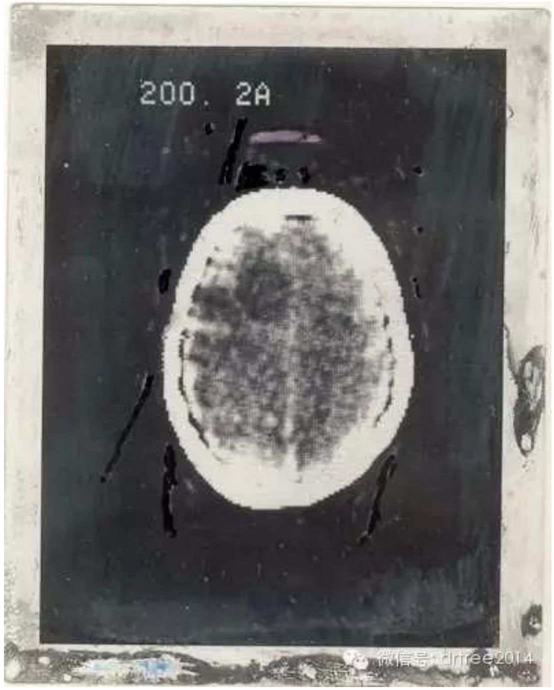
- February 1908, advertisement in Shun Pao (申報), Shanghai, “洞穿臟腑之奇光”

戊申正月十五日
申報第一
洞穿臟腑之奇光
準於本月十六日起
登報聲明
崔大房仙傳半夏
東方雜誌丁未年第十二期
吃鴉片之人不可不一試
春陽社演劇廣告
不平則鳴
艮濟公司白
請試氣急消痰半夏包能除根永不再發

CT scan

- Computed Tomography (CT): The x-ray source produces a thin beam that is detected on the opposite side of the subject by an array of several hundred detectors in a line.
- Each detector measures absorption along a line through the subject which is then processed by a computer.
- Tumors too small to be seen with older x-ray techniques can be detected by CT scan

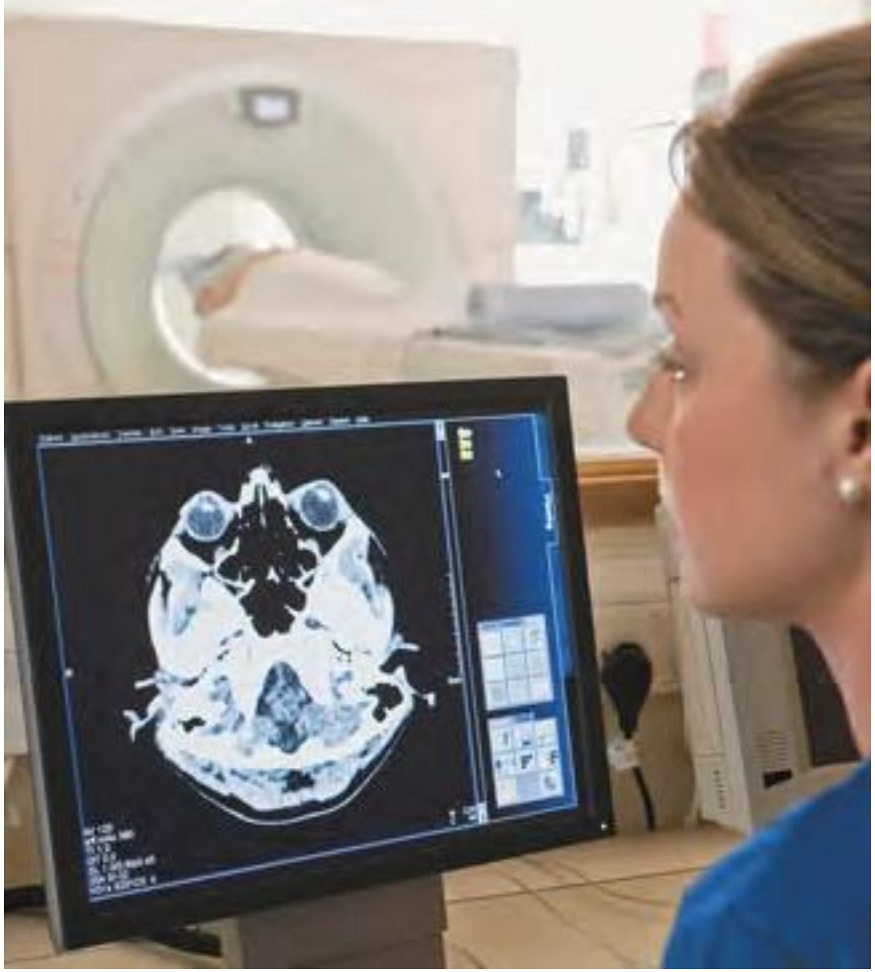
Early CT scanner in use, 1980.



The first clinical CT scan: Atkinson Morley's Hospital, October 1971

CT scan

- This radiologist is operating a CT scanner (seen through the window) from a separate room to avoid repeated exposure to x rays.



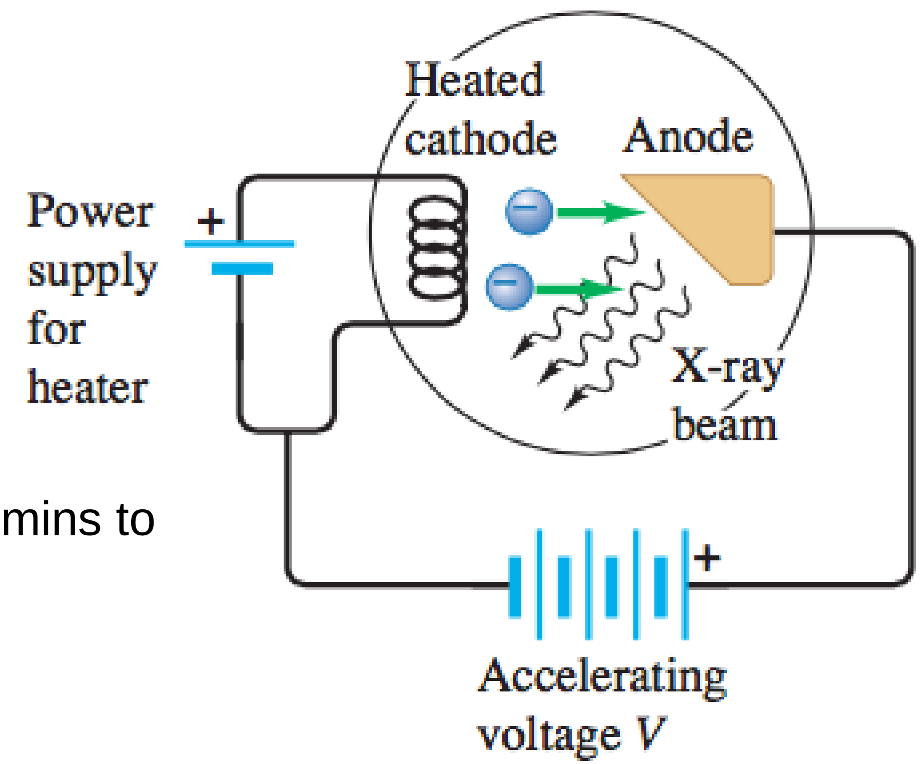
X-ray and the airport security

X-ray can cause damage

- X rays cause damage to living tissues.
- As x-ray photons are absorbed in tissues, their energy breaks molecular bonds, which can disturb the molecular structure of proteins and especially genetic material.
- Young and rapidly growing cells are particularly susceptible, which is why x rays are useful for selective destruction of cancer cells.
- Conversely, however, a cell may be damaged by radiation but survive, continue dividing, and produce generations of defective cells; thus x rays can cause cancer.
- Even when the organism itself shows no apparent damage, excessive exposure to x rays can cause changes in the organism’s reproductive system that will affect its offspring.
- A careful assessment of the balance between risks and benefits of radiation exposure is essential in each individual case.

Quiz

Test Your Understanding of Section 38.2 In the apparatus shown in Fig. 38.7, suppose you increase the number of electrons that are emitted from the cathode per second while keeping the potential difference V_{AC} the same. How will this affect the intensity I and minimum wavelength λ_{min} of the emitted x rays? (i) I and λ_{min} will both increase; (ii) I will increase but λ_{min} will be unchanged; (iii) I will increase but λ_{min} will decrease; (iv) I will remain the same but λ_{min} will decrease; (v) none of these.



Please email your answer within 5 mins to our TA:
TONG Qing
qtong7-c@my.cityu.edu.hk