Chapter 27

Quantum Optics

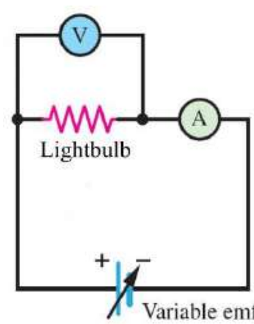
27.1 Black body radiation

27.1.1 Observe and explain

Lab or class

You friend Audrey wants to investigate how the power emitted by a hot object depends on the temperature of the object. She learned that tungsten is the metal that has highest melting point. Therefore, she decides to use the tungsten filament in the lightbulb of an overhead projector as the emitting object in her experiments (see the figure on the right; note: the filament is flat, not cylindrical).

Audrey obtains a tungsten filament lightbulb, an ammeter, a voltmeter and a variable voltage DC power supply. She connects these elements as shown in the next figure on the right and measures the current I through the lightbulb at different values of the potential difference ΔV across the lightbulb (columns 1 and 2 in the table below). Using these data, she calculates the resistance of the filament R_{filament} and the power output of the light bulb P for each measurement (columns 3 and 4).



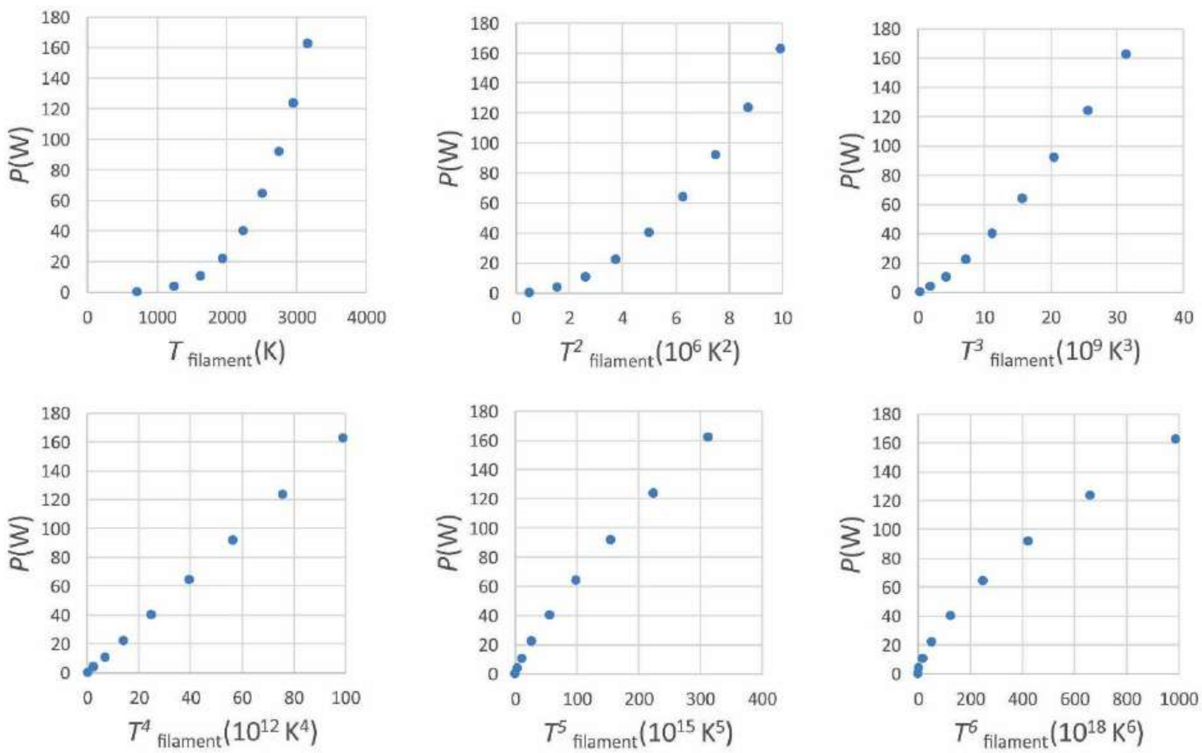
On the Internet, she finds the following empirical expression that relates the approximate temperature of the tungsten wire with the ratio $R / R_{300\text{ K}}$, where R is the resistance of the wire at temperature T, and $R_{300\text{ K}}$ is the resistance of the wire at about 300 K (room temperature):

$$T = [(175.49\text{ K})/\Omega] \times R + 207.27\text{ K}$$

Learning this, she comes up with an idea to use this relationship to estimate the temperature of the tungsten filament in her experiments. Using an ohmmeter, she measures the resistance of the lightbulb filament at room temperature, $R_{300\text{ K}} = 0.120\ \Omega$. She writes the ratios $R/R_{300\text{ K}}$ and corresponding estimated temperatures of the tungsten filament in columns 5 and 6.

(1)	(2)	(3)	(4)	(5)	(6)
ΔV(V)	I(A)	$R_{\text{filament}}(\Omega)$	P(W)	$R_{\text{filament}} / R_{300\text{ K}}$	T_{filament}(K)
0.35	1.02	0.34	0.4	2.86	710
1.66	2.34	0.71	3.9	5.91	1248
3.20	3.32	0.96	10.6	8.03	1621
5.12	4.35	1.18	22.3	9.81	1934
7.46	5.40	1.38	40.3	11.51	2235
10.04	6.41	1.57	64.4	13.05	2506
12.60	7.30	1.73	92.0	14.38	2740
15.22	8.14	1.87	123.9	15.58	2952
18.08	9.00	2.01	162.7	16.74	3156

After collecting and calculating all these data, she decides to test several mathematical models for the relationship $P(T_{\text{filament}})$, which she is seeking. Using data from the table she draws six graphs, each for a different power-law relationship between P and T_{filament}:



a. Explain how Audrey determined the values in columns 3 and 4 and which physical laws or definitions she used. Which assumptions did Audrey need to make to attribute the values in column 3 to the resistance of the filament?

b. You learned in Chapter 19 that the resistance of a metal increases with increasing temperature. Is the empirical equation for tungsten above consistent with this property of metals? Explain and provide quantitative arguments.

c. Based on the graphs shown above, write the mathematical model (a function) that best describes the P-versus-T_{filament} relationship.

d. Discuss under which assumptions the model that you suggested in part **c**. describes the relationship between the power emitted by the bulb in the form of electromagnetic waves and the temperature of the bulb's filament.

e. Read Section 27.1 in the textbook and then estimate the surface area of the filament in the bulb used in the experiments above. Evaluate the result.

27.1.2 Reading exercise

Interrogate Section 27.1 and answer Review Question 27.1.

27.2 Photoelectric effect

27.2.1 Observe, explain, and test your explanations

PIVOTAL Class: *Equipment (one set-up for the whole class):* an electroscope with a zinc plate on top (freshly polished), woolen cloth, plastic (PVC) bar, acrylic bar, a source of visible light and a source of UV light. Alternatively, watch the video at https://youtu.be/X7EQJU9bxV4

a. Watch your instructor touch the metal plate on the top of an electroscope with a negatively charged bar and rub it against the plate (rubbing is necessary to "transfer" more charge from the charged object to the electroscope). Note what happens to the electroscope leaves in each case. Work with your neighbors to come up with an explanation for the outcome of each experiment.

The experiment	Outcome of experiment	Explanation
1. Rub the metal plate with a negatively charged PVC bar. Then remove the bar. (The PVC bar is charged negatively if rubbed with wool.)	The leaves remain deflected for a long time.	
2. Rub the metal plate with a negatively charged PVC bar. Then remove the bar. Then shine a flashlight on the metal plate.	The leaves remain deflected for a long time.	
3. Rub the metal plate with a negatively charged PVC bar. Then remove the bar. Then shine an ultraviolet (UV) light on the metal plate.	The electroscope discharges (as indicated by the leaves moving together).	

The discharge of the negatively charged electroscope due to exposure to light is called the *photoelectric effect.*

b. Two students who observed the same set of experiments came up with the following explanation: UV light consists of vibrating electric and magnetic fields. The electric field exerts a force on the electric charges in atoms of the air, ionizes air and ionized air is a conductor. That is why the electroscope discharges. Design an experiment that they can perform to test this explanation.

c. The students came up with the following experiment: Shine UV light on the positively charged electroscope. What does their explanation predict for the positively charged electroscope?

d. Watch the outcome and compare it to the prediction: https://youtu.be/EgxVXOnsFx0

e. Now that they have rejected the ionized air explanation, the students came up with a new explanation: Maybe UV light kicks electrons out of the zinc plate? They even came up with an experiment to test it! They decided to shine UV on a neutral electroscope. Why would they do that and what prediction did they make before they performed the experiment?

f. Now they performed the experiment https://www.youtube.com/watch?v=eKhZoCrG0C8 Did the outcome match their prediction?

g. Rather disappointed they started thinking why their experiment did not match the prediction. They started thinking about what they knew about the structure of metals. How does their knowledge about the structure of metals might help them explain why their experiment did not turn out as expected?

i. Luckily, their teacher helped them and ran the following experiment: https://youtu.be/8hGBUeszdCE Explain why the teacher did this experiment and what could the students conclude from it?

j. Think of how you can test that the neutral electroscope was really charged positively by the UV light.

k. Compare your ideas for the experiment with the one we recorded. https://youtu.be/bwGF-gIqLPY

27.2.2 Explain

PIVOTAL Class

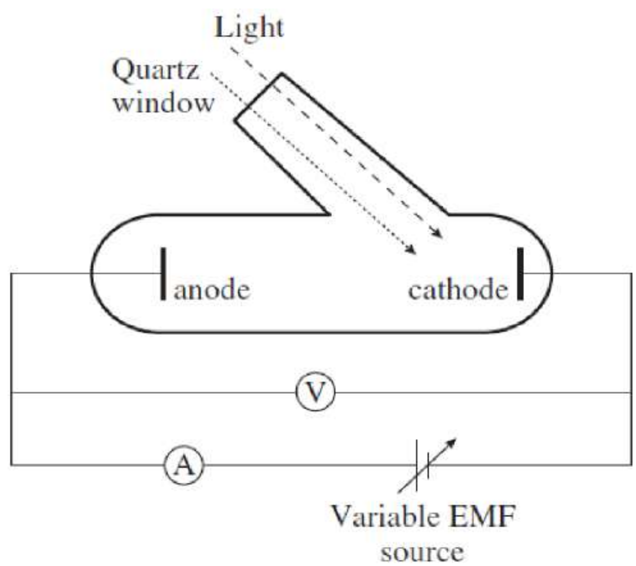
Assume you know that free electrons inside metals can move and positively charged ions cannot. Assume that light is an electromagnetic wave in which $\vec{E}$ and $\vec{B}$ fields oscillate periodically.

Use your knowledge of the effects of the electric field on charged particles to explain the effect of the light on the negatively and positively charged metal surface in Activity 27.2.1.

27.2.3 Observe and explain

PIVOTAL Class

Physicists use an evacuated glass container such as the one shown below to study the photoelectric effect. Light of different frequencies can shine through a quartz window onto a metal plate connected to the negative pole of the battery. Such a plate is called the *cathode*. The other plate inside the tube is connected to the positive side of the battery and is called the *anode*. In our experiments the anode and the cathode are always made of the same material. When no UV light shines on the cathode, the ammeter does not register any current. Work with your group members to answer the following questions.



a. When a UV light shines on the cathode, the ammeter registers a current in the circuit. Explain how UV light can cause the current. *Note*: A voltmeter has very high electrical resistance.

b. When the battery is replaced with a wire but the UV light still shines on the cathode, the ammeter registers a small current—much smaller than in part **a**. Explain.

c. If the polarity of the battery is reversed, then the plate on which the light shines is at a higher potential than the plate on the left side. When this reversed potential difference reaches a certain value, the ammeter reading drops to zero. Explain why. (This potential difference is called a *stopping potential*, V_s.)

27.2.4 Observe and explain

PIVOTAL Lab

In this activity you will explore the photoelectric effect with a PhET computer simulation available at the following link https://phet.colorado.edu/sims/cheerpj/photoelectric/latest/photoelectric.html?simulation=photoelectric.

Run the simulation and see how you can change the following quantities and parameters:

- battery voltage
- the intensity of light
- the wavelength of light
- the metal from which the cathode is made

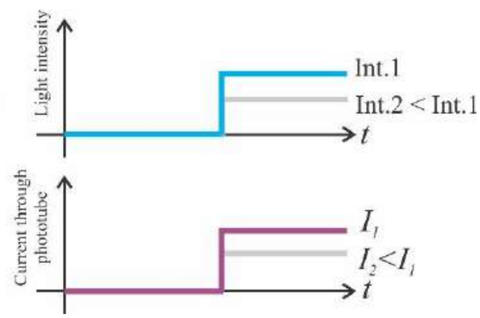
The table below describes various experiments with a phototube carried out by Philip Lenard at the end of the 19th century. Use the PhET simulation to perform the experiments (except the last one).

a. Perform the first three experiments described in the first column. Sketch the graphs that you obtain in the second column. In the last column, write explanations for the observed dependencies and for the given dependency (experiment d.). Try to explain the results of the experiments with the **electromagnetic wave model of light.** Write your explanations in the space *above* the line that divides each cell.

SETTINGS: For all experiments, use a **sodium cathode** and a wavelength of light of **350 nm** (if you click on the number, you can enter any wavelength value).

Experiment	Observed result	Try to explain the observed features of the graphs
1. Select (tick) Current vs light intensity graph. Set the battery voltage to the maximum positive value (+8.0 V). Plot the graph by changing the light intensity with the Intensity slider	*Sketch a graph*	
2. Select Current vs battery voltage graph. Set the light	*Sketch a graph*	

intensity to the maximum value. Plot the graph by using the slider on the battery to change the battery voltage from +8.0 V to -8.0 V. Take a picture of the graph by clicking on the icon with the camera image. (Note: when the battery voltage is zero, the battery behaves like a wire with no resistance.)		______________________
3. (Continuation of the previous experiment) Reduce the light intensity to about 2/3 of the maximum value and repeat the procedure described in the previous step. Record the graph again. Then reduce the intensity to 1/3 of the maximum value, repeat the experiment and record the third graph.	*Sketch the three resulting dependencies in a common graph.*	______________________
4. Change value of the wavelength to 550 nm and check if increasing the intensity of light allows you to detect current. Then try to find the smallest wavelength for which you can still detect the current		______________________

for the highest intensity of light.		
5. Description of the experiment (the simulation does not allow implementation of this experiment) We measure the time elapsed from the moment the lamp is switched on to the moment the current through the phototube is detected and how this time depends on the intensity of the light.	**The current is observed to appear without any delay, even at the lowest light intensity.** 	

b. Referring to the apparatus in Activity 27.2.3, the current is stopped when the metal cathode on which the light shines is at a positive potential relative to the more negative potential of the plate on the left side.

c. Surprisingly, you find that the potential difference that stops the current (see Activity 27.2.3 part **c** and Activity 27.3.4 experiment 3) does *not* depend on the intensity of light. The electric current induced by high-intensity light is stopped as easily as electric current induced by low-intensity light. Explain this observation.

d. While the stopping potential does not depend on the intensity of light, it does depend on the color: the higher the light frequency (UV versus visible, violet versus red), the higher the stopping potential. How can you explain this observation?

27.2.5 Explain

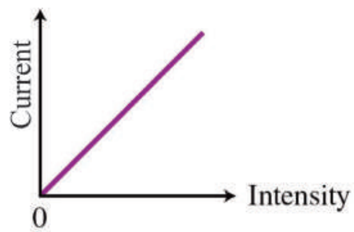
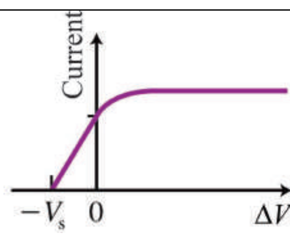
PIVOTAL Class

You observed in Activity 27.2.1 that visible light does not discharge a negatively charged electroscope. The increase of the intensity of visible light does not make a difference—no current is observed. However, even at very low intensity, UV light discharges a negatively charged electroscope. Can you explain it using an electromagnetic wave model of light? Elaborate.

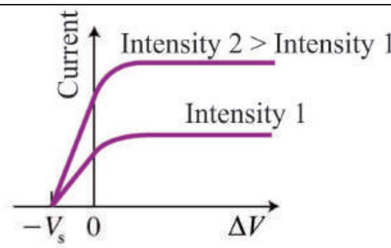
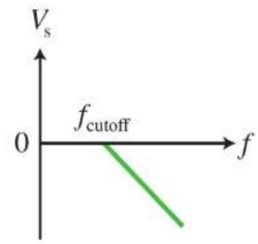
27.2.6 Observe and explain (a version of 27.2.4 without the simulation)

PIVOTAL ***Class***

In the table below try to use the *wave model* of light to explain each of the experimental results involving the apparatus shown in Activity 27.2.3.

<table>
<tr><th>Experiment</th><th>Result</th><th>Explain using the wave model</th></tr>
<tr><td>a. As the light intensity increases, the electric current changes as shown in the graph.</td><td>
</td><td></td></tr>
<tr><td>b. The dependence of the electric current on the potential difference across the electrodes is shown. Explain the steady part of the graph. The intensity of light remains constant during the experiment.</td><td>

Note: ΔV is positive when the right metal plate (the cathode) connects to the positive battery terminal.</td><td></td></tr>
<tr><td>c. Use the wave model to try to explain why the current decreases to zero when there is a negative stopping potential difference $-V_s$ in experiment b.</td><td></td><td></td></tr>
</table>

d. You repeat the previous experiment for increasing intensity light. The stopping potential difference $-V_s$ does not change.		
e. The potential difference $-V_s$ needed to stop the electric current depends on the light frequency—see the graph.		

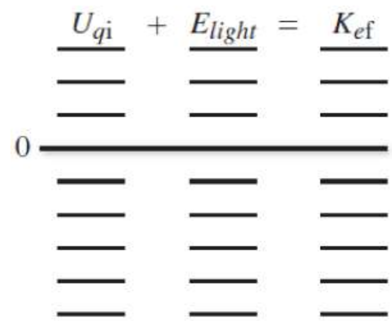
27.3 Quantum model explanation of the photoelectric effect

27.3.1 Represent and reason

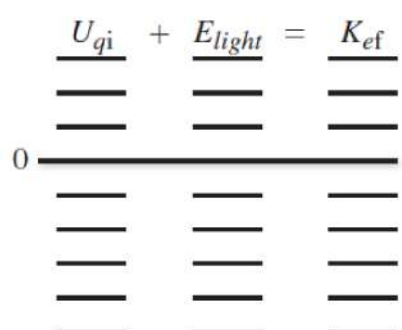
Class: *Equipment per group:* whiteboard and markers.

Analyze and represent the following two historical findings:

a. In 1902 the German physicist Phillip Lenard suggested an explanation for the photoelectric effect. He proposed that light, being an electromagnetic wave, knocked out electrons from the surface of the cathode by continuously exerting force on the electrons. These electrons were then accelerated by the electric field of the battery inside the glass tube, reached the opposite electrode and closed the circuit. He reasoned that if the energy of interaction between electrons and the lattice is negative and equal to $-\phi,$ and light had the energy E_{light} larger than $\phi,$ then the leftover energy of light would be given to the electrons in the form of kinetic energy $K_f.$ Draw a new energy bar chart that represents this energy exchange process between light and electron-lattice system during the photoelectric effect. Remember that light energy is continuously coming toward the cathode, therefore the bar for light energy is continuously growing.



b. In 1905 Albert Einstein suggested that the photoelectric effect can be explained assuming that light is a stream of bundles of energy (photons), which are individually absorbed by electrons in the metals. The energy of each photon is determined by the frequency of light ($E = hf$, where $h = 6.63\times10^{-34}\,\text{J}\cdot\text{s}$); the higher the frequency, the higher the photon energy. An electron is bound to the crystal lattice, and the energy of the interaction of one electron with the lattice is $-\phi$. An electron can absorb **only the energy of one photon**. Draw a new energy bar chart that represents the energy exchange process between a photon and an electron-lattice during the photoelectric effect, with the initial state the electron being in the metal and the final state it being outside the metal.



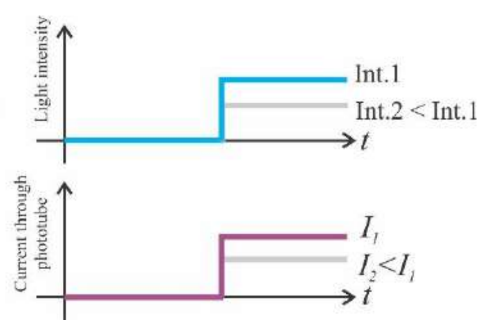
c. Discuss with your group members the fundamental differences between two explanations and whether each of them accounts for all observational evidence collected for photoelectric effect.

27.3.2 Observe and explain

PIVOTAL Lab

Use the photon model to try to explain the results of the five experiments in Activity 27.2.4 using the bottom cells in the right column in the table below. Before starting, carefully describe the new model.

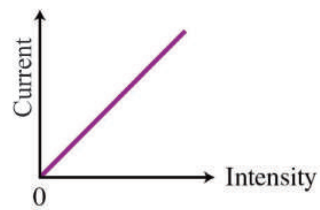
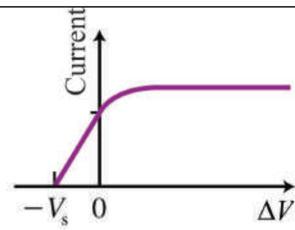
Experiment	**Observed result**	**Try to explain the observed features of the graphs**
1. Select (tick) Current vs light intensity graph. Set the battery voltage to the maximum positive value (+8.0 V). Plot the graph by changing the light intensity with the Intensity slider	*Sketch a graph*	Higher intensity => higher E, B, larger forces on *e*, more *e* exit from cathode per sec, larger current I
2. Select Current vs battery voltage graph. Set the light intensity to the maximum value. Plot the graph by using the slider on the battery to change the battery voltage from +8.0 V to -8.0 V. Take a picture of the graph by clicking on the icon with the camera image. (Note: when the battery voltage is zero, the battery behaves like a wire with no resistance.)	*Sketch a graph*	$U>0$: all *e-s* that exit from the cathode arrive at the anode $U<0$: the force *Ee* is exerted on *e-s* pointing to the left =>fewer *e* reach the anode
3. (Continuation of the previous experiment) Reduce the light intensity to about 2/3 of the maximum value and repeat the procedure described in the previous step. Record	*Sketch the three resulting dependencies in a common graph.*	Higher intensity => more *e* per sec exit the cathode=> larger current I IT DOES NOT EXPLAIN why the stopping potential is the same for all intensities.

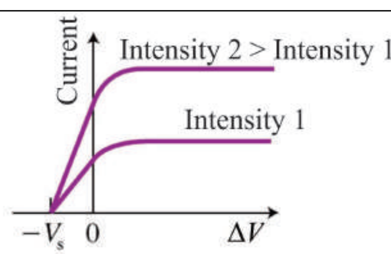
the graph again. Then reduce the intensity to 1/3 of the maximum value, repeat the experiment and record the third graph.		
4. Change value of the wavelength to 550 nm and check if the increasing the intensity of light allows you to detect current. Then try to find the smallest wavelength for which you can still detect the current for the highest intensity of light.		Wave model DOES NOT EXPLAIN it. According to the wave model, the more intense light has more energy and should eject electrons.
5. Description of the experiment (the simulation does not allow implementation of this experiment) We measure the time elapsed from the moment the lamp is switched on to the moment the current through the phototube is detected and how this time depends on the intensity of the light.	**The current is observed to appear without any delay, even at the lowest light intensity.** 	NOT EXPLAINABLE: we would expect a delay at very low intensities

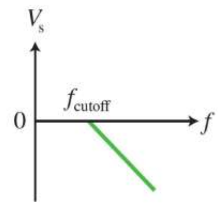
27.3.2 Observe and explain (a variation without the PHET simulation)

***PIVOTAL* Class**

Use the photon model to try to explain the results of the five experiments in Activity 27.2.6. Before starting, carefully describe the new model.

Experiment	**Result**	**Explain using the photon model.**
a. As the light intensity increases, the electric current changes as shown in the graph.		
b. The dependence of the electric current on the potential difference across the electrodes is shown (measured by the voltmeter) while the intensity of light remains constant. Explain the steady part of the graph.	 `Note:` ΔV is positive when the right metal plate (the cathode) connects to the positive battery terminal.	

Experiment	**Result**	**Explain using the photon model.**
c. Use the photon model to explain why the current decreases to zero when there is a negative stopping potential difference $-V_s$ in experiment **b**.		
d. You repeat the previous experiment for increasing intensity light. The stopping potential difference $-V_s$ does not change.		

e. The potential difference $-V_s$ needed to stop the electric current depends on the light frequency—see the graph.		

27.3.3 Test your ideas

So far, we have used Einstein's idea explaining photoelectric effect by applying it to the experiments that we have observed before. As you know, in physics, one needs to test new ideas by using them to predict the outcomes of the new experiments. Here is a testing experiment that was conducted by Robert Millikan who actually did not like the quantum explanation of photoelectric effect and wanted to disprove it. He said that if he finds the longest wavelengths of light cause photoelectric effect in different metals for which he knows the work functions, he could use these data to calculate the value of the Plank's constant. If Einstein is correct, this value should come out to be the same for different metals, but this should not happen, thought Millikan. Here are his data:

Metal	**Work function (eV)**	λ_{max} (nm)	**Color or type of light**
Aluminum	**4,06**	**305**	**UV**
Sodium	**2,3**	**539**	**green**
Cesium	**2,1**	**590**	**Yellow**
Lead	**4,14**	**300**	**UV**
Magnesium	**3,66**	**339**	**UV**
Zinc	**4,3**	**288**	**UV**

a. Did Millikan disprove Einstein's equation for photoelectric effect?

b. Discuss the following question in your group and suggest possible answers/explanations: The experiments with the electroscope (see Activity 27.2.1) are always done with a zinc sphere or plate. Why are we not using aluminum or magnesium, which have a lower work function than a zinc plate? (*Hint:* Think what can happen to light falling on a metal?).

27.3.4 Reading exercise

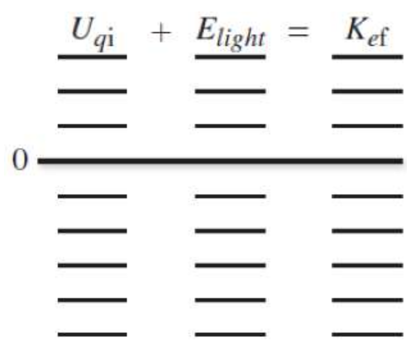
Interrogate Section 27.3 in the textbook and answer Review Question 27.3.

27.4 Photons

27.4.1 Represent and reason

PIVOTAL Class: *Equipment per group:* whiteboard and markers.

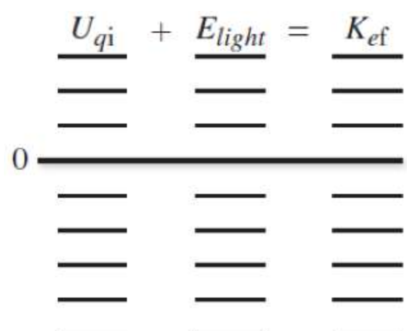
Draw an energy bar chart to represent the following process: a photon of light hits a metal, the energy of the photon is exactly equal to the magnitude of the negative electric potential energy of the interaction between the electron and the lattice.



27.4.2 Represent and reason

PIVOTAL Class: *Equipment per group:* whiteboard and markers.

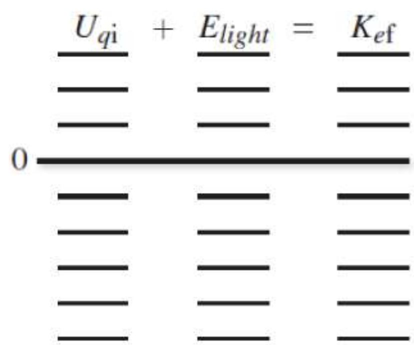
Draw an energy bar chart to represent the following process: a photon of light hits a metal and ejects an electron with zero kinetic energy.



27.4.3 Represent and reason

PIVOTAL Class: *Equipment per group:* whiteboard and markers.

Draw an energy bar chart to represent the following process: a photon of light hits a metal and ejects a fast-moving electron.



27.4.4 Explain

Use the photon model of light to explain why light exerts pressure on a surface on which it shines. On what surface would the same photon exerts a greater pressure: a shiny one or a black one? Explain. *Hint:* Think about elastic collisions and inelastic collisions.

27.4.5 Test your ideas

PIVOTAL Class: *Equipment per group:* whiteboard and markers.

Light passes through double slits and illuminates a screen producing the double-slit interference pattern (shown on the right) observed and explained in Chapter 24 using a wave model of light. However, we now have experiments that can only be explained if we consider light to be a stream of photons—a photon model for light.

a. First use the wave model of light to predict what you expect to observe on the screen if you illuminate the double slits with very low intensity light. Then use the photon model of light to make a prediction.

b. Reconcile these two models of light with the outcome of this experiment, which is described in the textbook in Testing Experiment Table 27.7.

27.4.6 Evaluate

PIVOTAL Class: *Equipment per group:* whiteboard and markers.

Your friend Snehal says that the photon model of light is not a new model, but just an old particle-bullet model of light. How can you convince Snehal that his opinion is not correct?

27.4.7 Derive

***PIVOTAL* Class:** *Equipment per group:* whiteboard and markers.

We found that light exhibits a particle-like behavior when interacting with matter. If a photon has particle-like properties, it should have momentum.

a. Write an expression for the energy of a photon and set it equal to the relativistic energy of a particle with mass *m* moving at speed *c*. (Massive particles do not move at the speed of light, *c*. Here we are assuming that the photon is a particle moving at speed *c*.) Use this to determine an expression for the equivalent mass of a photon.

b. Write an expression for the momentum of a photon—it moves at speed *c* and has the equivalent mass *m* derived in part **a**. You should now have an expression for the momentum of a photon in terms of its frequency.

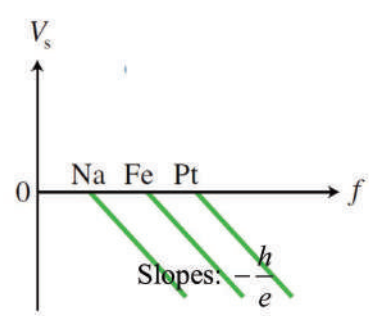
c. Rewrite this expression in terms of the wavelength of the photon.

d. Compare a photon to a classical particle—such as a billiard ball. What are the properties that are similar? What are the properties that are different?

27.4.8 Observe and explain

Class

The experiment described in Activity 27.3.2 part **e**. is repeated for different types of metal (both the cathode and anode are made of the same metal). The results are shown below. The work functions of several metals are given in the table below. Use the photon model of light to explain these observations.



Metal	Aluminum (Al)	Copper (Cu)	Iron (Fe)	Sodium (Na)	Platinum (Pt)	Zinc (Zn)
Work function (eV)	4.1	4.7	4.7	2.3	6.4	4.3

27.4.9 Practice

Class: *Equipment per group:* whiteboard and markers.

Use some of the information from Activity 27.4.8 to determine the minimum frequency light that will cause a photoelectric emission (a) from sodium and (b) from iron.

27.4.10 Represent and reason

A 200-nm light source shines on a sodium surface. Represent with a bar chart and an equation each of the processes described below.

a. The process starts with a 200-nm photon and ends just after the ejection from sodium of an electron that moves at maximum speed.

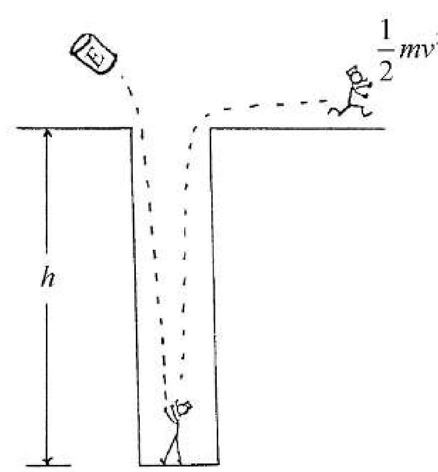
b. The same as above, only now the electron has traveled across the photoelectric tube. A potential difference has stopped the electron just before reaching the metal collector electrode.

27.4.11 Reason

Class: *Equipment per group:* whiteboard and markers.

In the literature, you can find the following mechanical analogy for the Einstein's equation that describes the energy changes in a photoelectric effect:

A student is trapped in a well with depth h (see figure below). A friend throws her a can of energy drink. When the student drinks the drink, she gets enough energy to climb out of the well. The rest of the energy she received from the drink goes for her kinetic energy when she climbs out of the well.



a. Identify and describe the relevant elements and/or relationships (including equations) in the base (analogy) and in the target.

Base	Target
Energy drink	
Energy to lift the student from the well (mgh)	
Student	
Earth	
Student's kinetic energy	
The well	

b. Describe the most important limitations of the analogy

Adapted from: Carl H. Hayn, »Analogy for Einstein's photoelectric equation«, *Phys. Teach*. **20**, 314 (1982)

https://doi.org/10.1119/1.2341044

27.4.12 Evaluate

***Class** Equipment per group:* whiteboard and markers.

Your friend Tamara is working on physics problems. She provides the following answer to the problem below. Evaluate the answer to see if you agree. If not, correct the answer.

The problem:

a. Light of unknown wavelength is incident on a copper cathode. The stopping potential difference is 3.0 V. What is the maximum speed of electrons leaving the copper cathode of work function 4.7 eV?

b. What is the wavelength of this light?

Proposed solution:

a. The electron's kinetic energy must have been enough to traverse a region with a $(4.7+3.0)\text{V}$ potential difference. Thus, using energy conservation we get:

$$\frac{1}{2}mv^2 = e\Delta V$$

or

$$v = \left(\frac{2e\Delta V}{m}\right)^{1/2} = \left(\frac{2\left(1.6\times 10^{-19}\ \text{C}\right)\left(7.7\ \text{V}\right)}{\left(9.11\times 10^{-31}\ \text{kg}\right)}\right)^{1/2} = 1.64\times 10^{6}\ \text{m/s}$$

The photon's energy equals the kinetic energy that the electron acquired from it, which equals the stopping energy of the electric potential difference:

$$hf = \frac{1}{2}mv^2 = \left(-e\right)\left(-V_{\text{s}}\right)$$

b. Note that $f = c/\lambda.$ Thus,

$$\lambda = \frac{hc}{eV_{\text{s}}} = \frac{\left(6.63\times10^{-34}\ \text{J}\cdot\text{s}\right)\left(3.0\times10^{8}\ \text{m/s}\right)}{\left(1.6\times10^{-19}\ \text{C}\right)\left(3.0\ \text{J/C}\right)} = 414\times10^{-9}\ \text{m} = 414\ \text{nm}$$

27.4.13 Explain

Class

You have a laser pointer. Remember that a laser can be considered as a light source that emits monochromatic light—light having a single frequency.

a. How is the color of the laser beam related to the energy of the photons?

b. How is the intensity of the light (energy/time) related to the number of photons per second?

c. How is the intensity of the light (energy/time) related to the frequency of the photons?

27.5 X-rays

27.5.1 Reading exercise

Interrogate Section 27.5 and answer Review Question 27.5.

27.5.2 Explain

Explain to your friend whether X-rays are dangerous and if they are dangerous, then what are the ways to protect us from these dangers?

27.6 Photocells, solar cells and LEDs

27.6.1 Observe and explain

***PIVOTAL* Lab:** *Equipment per group:* a red LED and a voltmeter (*do not* use an auto-range voltmeter!)

a. In a bright room, connect a red LED to a voltmeter (with no battery) and observe the reading on the voltmeter. Record your observations.

b. Devise an explanation or explanations for a non-zero reading of the voltmeter although it is not connected to a battery.

27.6.2 Test your idea

***PIVOTAL* Lab:** *Equipment per group:* the same as in Activity 27.6.1, and a flashlight.

a. Work with your group members to design an experiment or experiments to test the explanation(s) you devised for the experiments in Activity 27.6.1.

b. Conduct the experiment(s) and record the outcome(s). What is your judgment about the idea under test?

27.6.3 Apply

***PIVOTAL* Lab:** *Equipment per group:* two red LEDs, two green LEDs, a voltmeter (*do not* use an auto-range voltmeter!), various resistors, wires, and battery. (We recommend using clear plastic LEDs that are made by the same manufacturer, and have the same power angle and approximately the same nominal luminous intensity.)

a. Use the explanation that you have not ruled out in Activity 27.6.2 to investigate how the color of light and the intensity of light incident on an LED (detector) affect the voltage across that LED. Present your findings in a table. Investigate what happens when you shine red LED (source) on a red LED (detector), green LED on a red LED, red LED on a green LED, and green LED on a green LED (in every case the LED on which the light is shining is connected to a voltmeter). *Note*: The reading of the voltmeter may significantly depend on the relative orientation (incidence angle) of the source-LED with respect to the detector-LED. Vary the incidence angle and record the maximum voltmeter reading.

b. Compare your findings with our findings presented in the table below. Do your findings (qualitatively) agree with ours?

		Detector LED	
		Red	Green
Source LED	Red	1.60 V	0 V
	Green	1.52 V	1.78 V

27.6.4 Observe and explain

Lab: *Equipment per group:* several different LEDs, magnifying glass.

a. Observe different non-glowing LEDs with a magnifying glass and under a microscope.

b. Explain why the image of the interior parts of the LED is highly distorted.

27.6.5 Test your ideas

Lab: *Equipment per group:* several different LEDs, magnifying glass, and other equipment on request.

Design an experiment to test your explanation from the previous activity of why the image of the interior parts of the LED is distorted and come up with a method to see inside the plastic dome clearly. *Hint*: think about the refractive index of plastic. After you have come up with the method, watch the video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-27-6-5] and compare your idea with the one shown in the video.

27.6.6 Explain and test your ideas

Lab: *Equipment per class:* several different LEDs, hair dryer, ice water bath.

a. Observe the inside of an LED while it is glowing (after "canceling out" the plastic dome effect) – see the video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-27-6-6a]. Draw a detailed picture of what you see.

b. Consider a possible explanation: there might be a metal inside.

c. Come up with a way to rule out the metal-based explanation using the knowledge of LEDs that you already have (see Chapter 19). After you have come up with the idea, watch the video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-27-6-6b] and compare your idea with the one shown in the video.

27.6.7. Reading exercise

Interrogate Section 27.6 in the textbook.

a. Explain how an LED produces light when it is connected to a circuit.

b. Explain why an LED has an opening voltage.

c. Explain how an LED can work as a small solar cell when connected to a voltmeter.