Center for Nanoscale Systems

CNS Institute for Physics Teachers

Title:	**The Phantastic Photon**
Original: **Revision:**	1 June 2002 23 June 2008
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Appropriate Level:	Regents Physics
Abstract:	According to Einstein's theory, light is composed of particles called photons. The color of light determines the wavelength and energy of the photons. Students investigate these relationships by shining colored light from super-bright LEDs onto phosphorescent and fluorescent materials. They determine which LEDs activate glow-in-the dark tape, measure their wavelengths and calculate the photon energies. Students are then asked to apply their knowledge of photons to explain the behavior of fluorescent paints.
Time Required:	Two 40 minute class periods
NY Standards Met:	4.1a All energy transfers are governed by the law of conservation of energy. 5.3c On the atomic level, energy is emitted or absorbed in discrete packets called photons. 5.3d The energy of a photon is proportional to its frequency.
Special Notes:	**The Phantastic Photon** is a kit available from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/. It is also available commercially from West Hill Biological Resources, Inc., www.westhillbio.com.

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Behavioral Objectives

Upon completion of this lab, a student should be able to:

- define the terms: photon, discrete packet, excited state
- explain the basic concepts of the particle nature of light
- explain how energy, frequency, wavelength, and color of photons are related.
- describe the appearance of the spectra of LEDs
- solve basic problems using the formulas $c = f \cdot \lambda$ and $E = h \cdot f$.
- explain how phosphorescent and fluorescent materials are excited by light photons, and how the two forms of materials are different.
- explain how distance from a light source influences excitation of the illuminated surface.
- describe the appearance of materials containing excited quantum dots, and state the size-color relationship of quantum dots.

Class Time Required:

Two 40-minute periods.

Teacher Preparation Time:

Prep time is 5-10 minutes. Set out materials needed.

Materials Needed:

The Phantastic Photon kits are available through the CIPT lending library and can be requested on-line at our website www.cns.cornell.edu/cipt after receiving training. Kits are also available for purchase from West Hill Biological Resources at www.westhillbio.com. In addition, each student group needs a meter stick.

Assumed Prior Knowledge of Students:

- Relationship between frequency and wavelength ($f = c/\lambda$)
- Conservation of energy

Background Information for Teacher:

Fluorescent and phosphorescent materials are all around us. These materials contain molecules that can absorb photons. The molecule gains the energy of the photon it absorbs, which puts the molecule in an excited state. At a later time, the molecule loses some of its energy by emitting a visible photon of lower energy. These emitted photons are what make glow-in-the-dark objects glow and fluorescent materials look very bright.

The primary difference between fluorescent and phosphorescent materials is that phosphorescent materials typically take much longer to emit photons from the excited state. For example, glow-in-the-dark objects will continue to give off photons for minutes or even hours after exposure to light. In contrast, fluorescent molecules emit photons very quickly, within nanoseconds of absorbing a photon.

The reason phosphorescent molecules take a long time to return to the ground state is that the excited electron has the wrong spin. Recall that the Pauli Exclusion Principle forbids two electrons of the same spin to occupy the same state. If the excited electron has the same spin as the other electron in the lower energy level, it must flip its spin before it is allowed to occupy that energy level. Since interactions in which an electron flips its spin are very rare, the electron in the higher energy level has to wait a long time to lose its energy and give off a photon.

Students may wonder why fluorescent and phosphorescent materials emit photons of lower energy than what they absorb instead of emitting a photon at the same energy. In other words, some energy is lost; how is it lost and where does it go? The answer is that it isn't really lost. It just shows up in a different form. The molecules have many ways to transfer energy to the environment that do not involve emitting visible photons. The excited molecule might transfer some energy to a photon and some energy to its neighbors through atomic collisions. Another possibility is that the molecule might emit an infrared photon (not visible) and lose a small amount of energy, leaving it in an intermediate state.

Answers to Questions:

A. Glow-in-the-right color

Note #1: the LED's are not monochromatic; the listed wavelengths are the peaks of the intensity spectrums provided by the manufacturer.
Note #2: Although it is not the point of this lab, it is worth pointing out to students that we are using the first order antinodes, but higher orders are clearly visible.

LED color	Tape glows? (YES or NO)	LED wavelength (nm)
blue	*yes*	*472*
red	*no*	*660*
green	*yes (slightly)*	*525*
orange	*no*	*620*
infrared	*no*	*875*
violet	*yes*	*430*
yellow	*no*	*590*
ultraviolet	*yes*	*395*

B. Exploring the Wavelengths of Colors

1. What do you notice about the wavelengths of the LEDs that make the tape glow? *The wavelengths that make the tape glow are all relatively short, approximately 530 nm and shorter.*
2. Light is a form of energy. Which wavelengths do you think contain the most energy? Explain. *The shorter wavelengths must contain more energy because they caused the tape to glow brighter.*
3. Notice that the tape always glows the same color no matter what color activates it. Write the color that it glows *green or yellow-green*
4. Estimate the wavelength of light emitted by the tape _*~550 nm*

5. How does the *wavelength* of the light emitted by the glowing tape compare with the *wavelength* of the LED light used to activate the tape? *The wavelength of the light emitted by the tape is longer than all of the wavelengths that activated the tape.*
6. How do you think the *energy* of the light emitted by the tape compares to the *energy* of light from LEDs that activated the tape? *The energy of the light emitted by the tape is less than the energy of the light that activated the tape.*
7. Why do you think some of the colors of light did not activate the tape? *Some of the wavelengths did not have enough energy to activate the tape.*

C. This is intense!

Distance	Blue LED	Yellow LED	Red LED	Ultraviolet LED
0.01 m	*yes*	*no*	*no*	*yes*
0.10 m	*yes*	*no*	*no*	*yes*
1.0 m	*yes*	*no*	*no*	*yes*

1. Does the intensity of the LED light make a difference in *how brightly* the tape glows? Describe your results. *Yes. For colors that activated the tape, the greater the intensity of the LED light, the brighter the tape glowed.*
2. Does the intensity of the LED light make a difference in *whether* the tape glows or not? Describe your results. *No. Even low intensity light of the right color can make the tape glow.*
3. Do you think the tape would glow if it received only a single particle of light from the ultraviolet LED? *Yes.*
4. If the tape received only a single particle of light (a single photon), and if it did glow, do you think the glow would gradually fade dimmer, or do you think it would be a tiny, brief flash, and be done? Why? *Tiny, brief flash, and done. One photon absorbed by the tape will only excite one electron. One electron dropping lower in energy level will emit, at most, only one* ***visible*** *photon. Can the human eye detect one photon? No. The point to make here is that the light doesn't continue because the energy has been 'used up'.*

D. Look at What Popped Out!

1. Predict the color of light that will be emitted from the yellow fluorescent paint for each LED. Write your predictions in the table below. Then test your predictions using the LEDs and the spectrometer to analyze the color from the paint. Record your results below.

LED color	Predicted color of light from yellow paint	Observed color of light from yellow paint
Red	--	red
Orange	*orange*	*orange*
Yellow	*yellow*	*yellow*
Green	*yellow*	*yellow*
Blue	*yellow*	*yellow*
Violet	*yellow*	*yellow*
Ultraviolet	--	yellow

2. Why does the ultraviolet light get converted to yellow light by the yellow fluorescent paint, but the red light remains red? *The ultraviolet light has enough energy to activate the fluorescent paint and make it emit yellow light. The red light does not have enough energy and simply gets reflected.*
3. White light is composed of all colors of light. Explain why white light makes yellow fluorescent paint look so intensely yellow. *All wavelengths of light shorter than yellow get converted to yellow light. Therefore, the yellow fluorescent paint can emit more intense yellow light than originally present in the incident light.*
4. Predict the color of light that will be emitted from the *different* fluorescent paints for a *green* LED. Write your predictions in the table below. Then test your predictions using the *green* LED and the spectrometer to analyze the color from the paint. Record your results below.

Paint color	Predicted color of light from paint	Observed color of light from paint
Red	*red*	*red*
Orange	*orange*	*orange*
Yellow	*yellow*	*yellow*
Green	*green*	*green*
Blue	*green*	*green*

5. Explain your observations from question 4. *Each fluorescent paint emits light of its own color, provided the incident light has great enough energy to activate the paint. Green has enough energy to activate red, orange and yellow paints. It does not have enough energy to activate green or blue paint, so the green light is simply reflected.*

E. Quantum Dots

1. What colors of light did each of the four quantum dot samples emit?

This will depend on the samples provided in your kit.

- *Solid samples: red-orange, orange, yellow, lime green, aqua blue (blue quantum dots are difficult and costly to produce, and hence are not very common.)*
- *Liquid samples: red-orange, orange, yellow, lime green*

2. Which quantum dots have the largest diameter? Which have the smallest? Why?

The color of a quantum dot depends on its diameter. Larger quantum dots emit lower energy (longer wavelength) light. The largest quantum dots in our sets will emit red-orange light and the smallest quantum dots will emit aqua blue light (smallest diameter, smallest wavelength, largest energy.)

3. Predict which quantum dots will be excited for each LED. Write your predictions in the table below. Then test your predictions and record your results below.

LED color	**PREDICTIONS** List the quantum dots you **expect** will be excited by each LED	**OBSERVATIONS** List the quantum dots that **are** actually excited by each LED
Red		*None*
Orange		*None*
Yellow		*red-orange, orange*
Green		*Red-orange, orange, yellow* *Green (liquid only)*
Blue		*Red-orange, orange, yellow* *Green (liquid only)*
Violet		*Red-orange, orange, yellow* *Green (liquid and solid)*
Ultraviolet		*All*

4. Explain your observations. Why can't the red LED excite the green quantum dots? What determines whether a particular quantum dot will be excited by a particular LED?

The light photons exciting the quantum dots must have at least as much energy as the light photons the quantum dots will emit. A red LED can't excite a green quantum dot because its photons don't have enough energy to do so. A particular LED will excite a particular quantum dot if the LED's photon energies are greater than or equal to the necessary energy (corresponding to the quantum dot color).

F. Post-lab Questions

1. Complete the chart below by calculating the energy of a single photon of light for each of the LEDs in your set. Remember that the frequency of light f is related to its wavelength λ through the formula $f = c/\lambda$ where c is 3.0×10^{8} m/s.

LED color	Wavelength (nm)	Wavelength (m)	Frequency (Hz)	Photon energy (J)
infrared	*875*	8.8×10^{-7}	3.4×10^{14}	2.2×10^{-19}
red	*660*	6.6×10^{-7}	4.5×10^{14}	3.0×10^{-19}
orange	*620*	6.2×10^{-7}	4.8×10^{14}	3.2×10^{-19}
yellow	*590*	5.9×10^{-7}	5.1×10^{14}	3.4×10^{-19}
green	*525*	5.3×10^{-7}	5.7×10^{14}	3.8×10^{-19}
blue	*472*	4.7×10^{-7}	6.4×10^{14}	4.2×10^{-19}
violet	*430*	4.3×10^{-7}	7.0×10^{14}	4.6×10^{-19}
ultraviolet	*395*	4.0×10^{-7}	7.4×10^{14}	4.9×10^{-19}

2. As wavelength increases, what happens to the energy of a photon? *The energy of a photon decreases as wavelength increases.*
3. An the number of photons increases, what happens to the total energy of the light? *The total energy of the light increases with the number of photons.*

4. The red LED uses about 0.03W (1 W = 1 J/s) and converts most of this power into light. Estimate the number of photons per second produced by the red LED.

$$0.03\frac{\text{J}}{\text{s}} * \frac{1\,\text{photon}}{3.0\times10^{-19}\ \text{J}} = 1\times10^{17}\ \frac{\text{photons}}{\text{s}}$$

5. Using the concept of photons, explain why red light, even if it is intense, cannot make the glow-in-the-dark tape glow (emit light). *Intense red light is composed of many red photons, each with energy* 3.0×10^{-19} *J. Photons can only get absorbed one at a time, and each red photon does not have enough energy to activate the tape, which requires* ~3.5×10^{-19} *J, the color of yellow-green light.*
6. When the glow-in-the-dark tape absorbs blue photons, it emits lower energy yellow-green photons. If energy is always conserved, explain how the energy emitted can be less than the energy absorbed. *The extra energy is deposited in the glow-in-the-dark tape as heat, or increased kinetic energy of atoms and molecules.*
7. Using the concept of photons, explain why a yellow fluorescent highlighter appears much brighter than a regular yellow marker in normal lighting conditions.
8. In clubs, a black light (ultraviolet light) is sometimes used for special effect to make white clothing glow. Explain how this works.
9. Photoresist, a chemical used in making computer chips, changes its solubility when exposed to ultraviolet light. Why are cleanrooms where photoresist is used illuminated with yellow light? *The yellow light does not have as much energy as ultraviolet light and will not expose the photoresist unintentionally. Also the human eye is most sensitive to yellow light, so it allows workers to see well.*
10. A silicon photodiode used as a light detector can only absorb photons of energy greater than 1.1 eV. Will it absorb photons from the infrared LED? *Converting the threshold energy to Joules gives* $1.1\,\text{eV} * \frac{1.6\times10^{-19}\ \text{Joule}}{1\,\text{eV}} = 1.8\times10^{-19}\ \text{J}$

    As calculated in question 1, the energy of a photon from the infrared LED is 2.2×10^{-19} *J, which is above the threshold. Therefore, the silicon photodiode will absorb the photon from the infrared LED.*

Tips for the Teacher:

- One possibility to engage students and introduce this lab is to shine a black light on glow-in-the-dark objects and ask students what makes them glow. Another possibility is to shine the room lights and then a blacklight on a paper with fluorescent yellow ink and standard yellow ink from markers, and ask students to explain what they see.

- During this activity it is helpful to have the room lights off because the spectrum from the fluorescent lights can make it difficult to read the spectrometer. Instead, turn on the overhead projector, which has an incandescent bulb, and aim it at a nearby wall. It will provide enough light for student to read the lab.

- Lab teams might have some trouble with light coming from another lab team's LED cards. Tell them to block the side path to the diffraction grating with their hand. If a questionable spectrum disappears, it was from a light source other than their own.

- If the glow tape has received a lot of exposure to the ultraviolet light, shining a low energy LED such as the red LED may make the tape temporarily glow brighter, surprisingly appearing to activate the tape. In fact, the photons from the red LED are acting on molecules that are *already* in an excited state, helping them to lose energy more quickly and give off photons. If the red LED is held for a short time over the same part of the tape, that region quickly becomes dimmer than the rest of the tape as the excited molecules become depleted.

- In the activity entitled "This is intense!" it is helpful to cover half of the glow-in-the-dark strip at the greater distances so that a comparison of exposed and unexposed parts is possible.

- Note that white paper contains a fluorescent substance that helps it to appear whiter. Therefore, when making your own fluorescent paint cards, it is best to use off-white card stock. Also, when measuring the wavelength of the LEDs, avoid shining the light on white paper or any other fluorescent material, which can lead to an inaccurate measurement.

Equipment List

Item Number	Quantity	Item
1	1	Spectrometer
2	1	Phosphorescent tape
3	1	Quantum Dots
4	1	Power adapter (24V, 0.25A)
5	2	Alligator clip leads
6	1	LED board holder
7	1	Diffraction grating
8	1	LED board
9	1	Fluorescent paint card

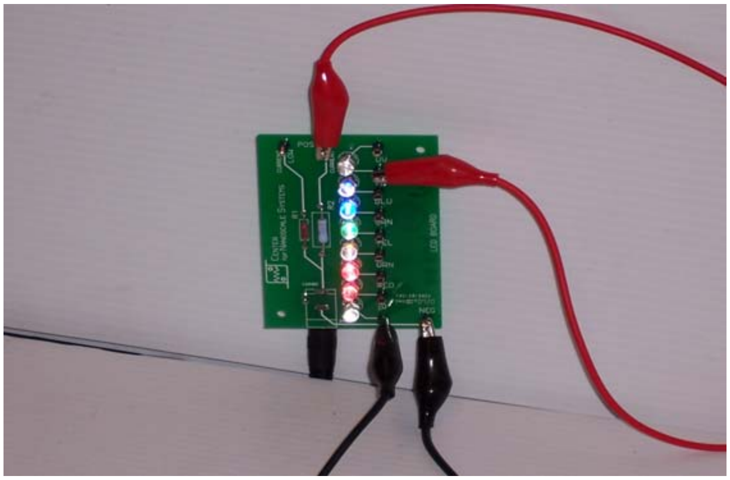
THE PHANTASTIC PHOTON

Why does ink from a fluorescent highlighter appear so bright? What makes glow-in-the-dark objects glow? How do optical brighteners in laundry detergent make your clothes look whiter? The answer to these questions can be found in the photon theory of light, first proposed by Albert Einstein in 1905. By exposing fluorescent and glow-in-the-dark materials to different colors and intensities of light, you will see photons at work.

Light Emitting Diodes (LEDs) - You have the LED card shown below. There are eight LEDs of different colors, as labeled on the right side. The 'UV' (ultraviolet) and 'IR' (infrared) LEDs emit most of their light at wavelengths your eye cannot see. The other six LEDs have the different colors of the rainbow.

Try to light up the blue LED as shown in the picture below:

- Disconnect any wires from the bottom of the LED circuit board and slide it out of the holder on the back of the spectrometer.
- Find the wall plug/power adaptor and the two hook-up wires (leads) with alligator clips. (We generally use red wires for positive and black wires for negative to make it easier to tell which wire is which, but the wire colors are not really important. Use the colors provided.)
  - Attach one alligator clip to the high current positive terminal on the top of the circuit board.
  - Attach the other end of that wire to top of the blue LED.
  - Attach one end of the second hook-up wire to the negative terminal in the bottom right hand corner of the circuit board.
  - Attach the other end of the second hook-up wire to the bottom of the blue LED.
- Plug the power adaptor into the bottom of the LED card near the "24V" DC power supply symbol and plug the other end into a wall socket. (The high current setting produces a constant current of about 20 mA flowing between the positive and negative leads and through anything to which the leads are attached.)



- Experiment with lighting up other LEDs. Can you light more than one at a time?

Disconnect a wire to turn off the LED card when you are not using it.

Warning!! Do not stare into the ultraviolet (UV) LED when it is lit. This can cause eye damage.

A. Glow-in-the-right color

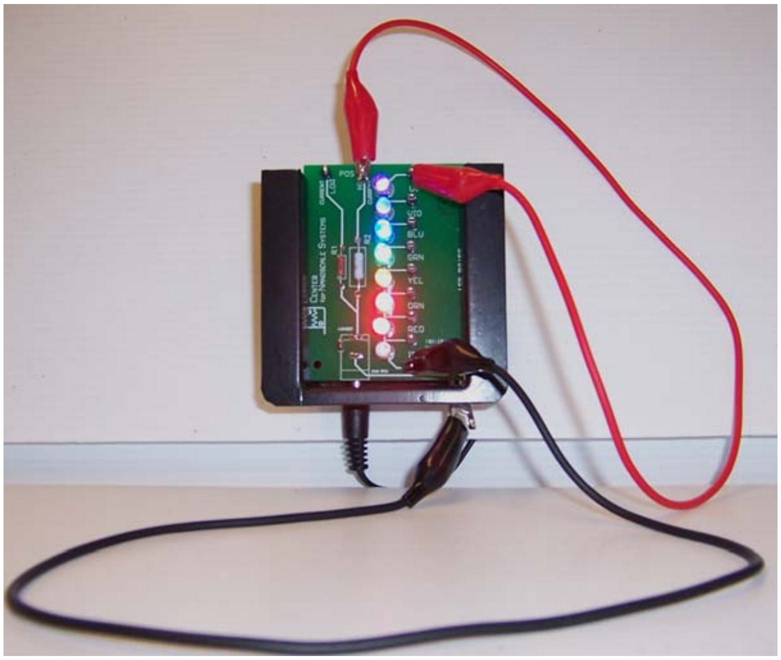
A glow-in-the-dark object only glows after it is exposed to light. How does the color of the light affect a glow-in-the-dark object? You can test this with the LEDs and piece of glow-in-the-dark tape enclosed in black paper.

- Hook up the blue LED using the "Hi" current setting.
- Shine the blue LED on the tape for a few seconds.
- Move the LED away from the tape and see if the tape is glowing.
- Record your observation for the blue LED, and then each LED color in the middle column of the table below ('yes' it makes the tape glow or 'no' it does not). If the tape glows, wait until it stops glowing before testing the next LED color (~ 30 seconds).

LED color	Tape glows? (YES or NO)	LED wavelength (nm)
blue		
red		
green		
orange		
infrared		875 nm
violet		
yellow		
ultraviolet		395 nm

B. Exploring the Wavelengths of Colors

- Disconnect the wires from the LED circuit board and slide it into the holder on the back of the spectrometer so that the LEDs face the slit.
- Reconnect the wires such that all the LEDs except the ultraviolet (U.V.) are lit. Use the "HI" current positive terminal, as shown in the picture. Note that the bottom wire connections are made through the holes in the bottom of the holder.



- Hold the spectroscope up and look through the diffraction grating (the slide mounted in the front). As you look towards the paper scale on either side of the LEDs, you should see the portion of the spectrum which is produced by each LED. If the bands of colors aren't horizontal, rotate the diffraction grating slide ¼ turn in the holder.
- Read the wavelengths of the six visible LEDs using the nanometer (nm) scales to the left and right of the LED strip. Since each LED produces a range of colors, use the center of the brightest color the LED produces. Record the wavelength you observe in the last column of the table in section A. (Hint: For some LEDs, the 'LOW' current setting will provide more accurate results.)

Answer the following questions:

1. What do you notice about the wavelengths of the LEDs that make the tape glow?

2. Light is a form of energy. Which wavelengths do you think contain the most energy? Explain.

3. Notice that the tape always glows the same color no matter what color activates it. Write the color that it glows ____________________.

4. Estimate the wavelength of light emitted by the tape _________________.

5. How does the *wavelength* of the light emitted by the glowing tape compare with the *wavelength* of the LED light used to activate the tape?

6. How do you think the *energy* of the light emitted by the tape compares to the *energy* of light from LEDs that activated the tape?

7. Why do you think some of the colors of light did not activate the tape?

C. <u>This is intense!</u>

The light from an LED gets more intense as you move the LED closer. Is intensity an important factor in whether or not the glow-in-the-dark tape glows?

- With the lights dimmed, place a piece of paper so that it covers half of the tape, blocking it from exposure to the LED light.
- Expose the tape for a few seconds to one combination of distance and color of LED at a time, as outlined in the table below.
- After each trial, remove the paper and immediately examine the entire tape to see if the paper left a shadow. If the exposed part of the tape is glowing; write "Yes" in the space provided. If there is no difference, the exposed tape is not glowing; write "No."

Distance	**Blue LED**	**Yellow LED**	**Red LED**	**Ultraviolet LED**
0.01 m				
0.10 m				
1.0 m				

<u>Answer the following questions:</u>

1. Does the intensity of the LED light make a difference in *how brightly* the tape glows? Describe your results.

2. Does the intensity of the LED light make a difference in *whether* the tape glows or not? Describe your results.

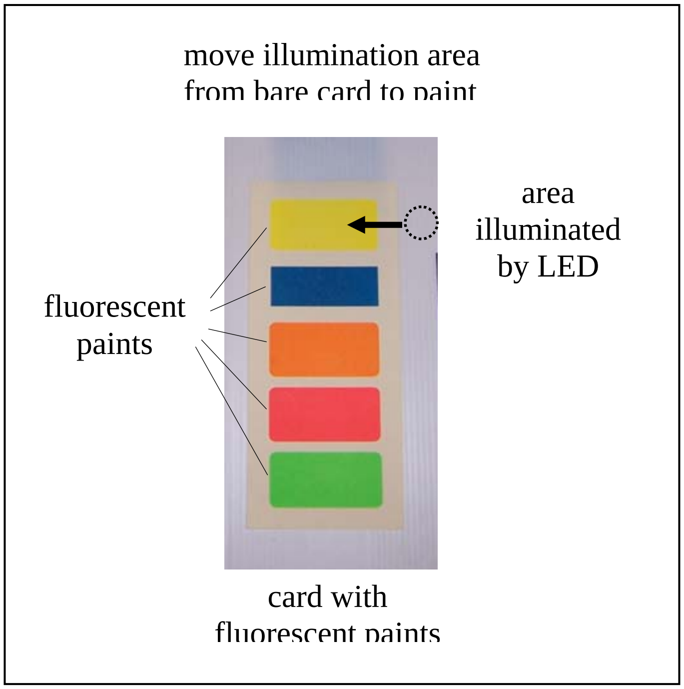
4. Do you think the tape would glow if it received only a single particle of light from the ultraviolet LED?

5. If the tape received only a single particle of light (a single photon), and if it <u>did</u> glow, do you think the glow would gradually fade dimmer, or do you think it would be a tiny, brief flash, and be done? Why?

D. **Look at What Popped Out!**

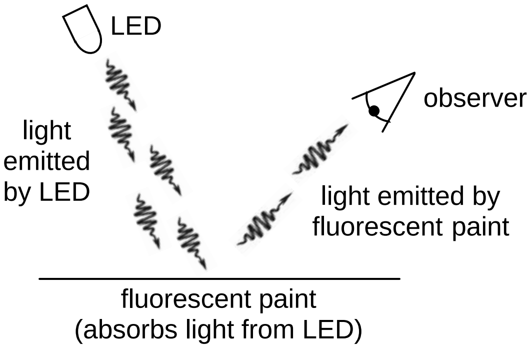
What makes fluorescent colors look so bright? Do fluorescent colors look bright in all kinds of light? You can test this with the LEDs and the manila card with different colors of fluorescent poster paint.

- Shine light from the UV LED on the fluorescent paints. Then shine light from the red LED on the fluorescent paints. Which light makes the paints "pop out" or look brighter?
- Let's take a closer look. Shine the light from the UV LED on the card where there are no paints. It should look violet. Now shine the light from the UV LED on the yellow fluorescent paint. The light should look yellow.



- Do the same thing with the red LED. Does the red light also change color on the yellow paint?
- Let's analyze this. Shine the light from the UV LED on the card where there are no paints. Take the spectrometer (without the LED holder) and aim it so that you can see pool of violet light on the card when you look through the diffraction grating and the slit. You should see the diffracted light fall on the scale to either side of the slit.
- Now shine the light from the UV LED on the yellow fluorescent paint. Aim the spectrometer at the yellow paint where the LED illuminates it. Did the wavelength of the light change?
- Try the same thing with the red LED, analyzing the light from the card and from the paint with the spectrometer. Does the wavelength shift as it did for the UV LED?

The diagram below shows that the light from the LED gets absorbed by the fluorescent paint. Then the paint emits light, some of which reaches your eye.



<u>Answer the following questions:</u>

1. Predict the color of light that will be emitted from the yellow fluorescent paint for each LED. Write your predictions in the table below. Then test your predictions using the LEDs and the spectrometer to analyze the color from the paint. Record your results below.

LED color	Predicted color of light from yellow paint	Observed color of light from yellow paint
Red	--	red
Orange		
Yellow		
Green		
Blue		
Violet		
Ultraviolet	--	yellow

2. Why does the ultraviolet light get converted to yellow light by the yellow fluorescent paint, but the red light remains red?

3. White light is composed of all colors of light. Explain why white light makes yellow fluorescent paint look so intensely yellow.

4. Predict the color of light that will be emitted from the *different* fluorescent paints for a *green* LED. Write your predictions in the table below. Then test your predictions using the *green* LED and the spectrometer to analyze the color from the paint. Record your results below.

Paint color	**Predicted color of light from paint**	**Observed color of light from paint**
Red		
Orange		
Yellow		
Green		
Blue		

5. Explain your observations from question 4.

E. Quantum Dots

Semiconductor nanocrystals or quantum dots are tiny nanometer-sized semiconductor particles (containing roughly 100 to 1000 atoms) that emit light when excited. Quantum dot diameters range from about 2 to 6 nm, which is about 40,000 times smaller than the diameter of human hair! These recently discovered structures emit a different color of light depending on the diameter of the nanoparticle, with larger diameter particles emitting lower energy light. You have four different samples of CdSe quantum dots, each containing millions of nanoparticles all of the same size.

- Shine light from the UV LED on the four quantum dot samples. This will excite the quantum dots. What colors do the quantum dots emit?
- Now shine light from the RED LED on the quantum dot samples. Can you excite the quantum dots with red light?

Answer the following questions:

1. What colors of light did each of the four quantum dot samples emit?

2. Which quantum dots have the largest diameter? Which have the smallest? Why?

3. Fill in the table below with your predictions of which quantum dots will be excited by each LED, and then test your predictions and record your observations.

LED color	**PREDICTIONS:** **List the quantum dots you expect will be excited by each LED**	**OBSERVATIONS** **List the quantum dots that are actually excited by each LED**
Red		
Orange		
Yellow		
Green		
Blue		
Violet		
Ultraviolet		

4. Explain your observations. Why can't the red LED excite the green quantum dots? What determines whether a particular quantum dot will be excited by a particular LED?

F. Post-lab Questions

According to Einstein's theory, light is composed of tiny particles called "photons." A photon is the smallest possible amount of light. You can think of it as a really tiny packet of energy. The energy of a single photon is proportional to the frequency of the light. If E is the energy of a single photon and f is its frequency, then

$$E = hf$$

where h is Planck's constant and is equal to $\mathbf{6.6 \times 10^{-34}}$ **J·s.**

1. Complete the chart below by calculating the energy of a single photon of light for each of the LEDs in your set. Remember that the frequency of light f is related to its wavelength λ through the formula $f = c/\lambda$ where c is 3.0×10^8 m/s.

LED color	Wavelength (nm)	Wavelength (m)	Frequency (Hz)	Photon energy (J)
infrared				
red				
orange				
yellow				
green				
blue				
violet				
ultraviolet				

2. As wavelength increases, what happens to the energy of a photon?

3. An the number of photons increases, what happens to the total energy of the light?

4. The red LED uses about 0.03W (1 W = 1 J/s) and converts most of this power into light. Estimate the number of photons per second produced by the red LED.

5. Using the concept of photons, explain why red light, even if it is intense, cannot make the glow-in-the-dark tape glow (emit light).

6. When the glow-in-the-dark tape absorbs blue photons, it emits lower energy yellow-green photons. If energy is always conserved, explain how the energy emitted can be less than the energy absorbed.

7. Using the concept of photons, explain why a yellow fluorescent highlighter appears much brighter than a regular yellow marker in normal lighting conditions.

8. In clubs, a black light (ultraviolet light) is sometimes used for special effect to make white clothing glow. Explain how this works.

9. Photoresist, a chemical used in making computer chips, changes its solubility when exposed to ultraviolet light. Why are cleanrooms where photoresist is used illuminated with yellow light?

10. A silicon photodiode used as a light detector can only absorb photons of energy greater than 1.1 eV. Will it absorb photons from the infrared LED?
(Hint: 1.0 J = 1.6×10^{-19} eV)