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# Quantum Dots and Colors Worksheet

## Background

Quantum dots are semiconducting nanoparticles that are able to confine electrons in small, discrete spaces. Also known as "zero-dimensional electronic structures," quantum dots are unique in that their semiconductor energy levels can be tailored by simply altering size, shape and charge potential. These energy levels result in distinct color identifications for different-sized quantum dots.

Semiconductors rely on electron excitation from the ground state into some excited energy level. The space between the excited and ground states is a characteristic energy band gap. When an electron is excited (ejected from ground state), a corresponding hole (positive charge) is left in the wake. The separation between the excited electrons (negative charge) sets up a potential difference. When this occurs and a circuit is completed, electron flow begins in the conductive band of the semiconductor. To re-establish the ground state, electrons and holes recombine, emitting photons over a wide and continuous wavelength range. However, this behavior in a bulk semiconductor primarily occurs over a range of energy levels and is limited by dimensions of the absorbing surface and range of incident photon wavelength.

Quantum dots offer a highly efficient process that mimics that of a bulk semiconductor but is quantized because of the length scales involved. "Quantum confinement" allows for quantum dots to be tailored to specific incident energy levels based on particle size. Additionally, nanoparticles offer superior surface area increases that enhance absorption properties per unit volume and/or conductive properties. Material scientists have found by varying quantum dot size, energy band gap size may increase or decrease. Larger size quantum dots create a decrease in energy band gap and emit large wavelength photons (red-shift). Small quantum dot sizes have an increase in energy band gap and emit short wavelength light (blue shift). This effect is demonstrated by quantum dot solutions of different particle sizes emitting different colors when exposed to a UV light source. Surface area effects enhance the efficiency of energy transfer properties, hence, quantum dots are known to have "high quantum yield." This also pertains to quantum dots emitting light long after exposure to a UV energy source.

Because of the unique quantum confinement effect, quantum dots are suitable for variety of applications, including medical and energy applications. Tumor or cancer detection is a primary application for quantum dots. Scientists attach different antibodies to specific proteins and release them. When quantum dots have permeated cell walls, scientists tag their locations through fluorescence imaging. Additionally, because of the high quantum yield, quantum dots remain fluorescent over time, making them useful for imaging purposes. Solar energy is another targeted application for quantum dots. Specifically, quantum dots are of interest for their exceptional and tailored light optical properties. Additionally, a robust solar cell may be easily manufactured consisting of optical layers of differing quantum dot sizes to absorb specific incident photons. This allows solar cells to utilize all wavelengths of light provided by the Sun, boosting solar cell efficiencies.

These are only a few of numerous applications. However, to really understand quantum dots, you must observe them first-hand. This activity provides the basis for understanding how these tiny optical beacons have the potential to become important to our way of life in the near future. As scientists and engineers, it is important to record all observations and draw conclusions from those observations. So observe carefully and have fun!

## Materials

- black box with viewing slot and vial holder
- black light with cord
- stopwatch
- quantum dots (get from the instructor)

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## Pre-Activity Questions

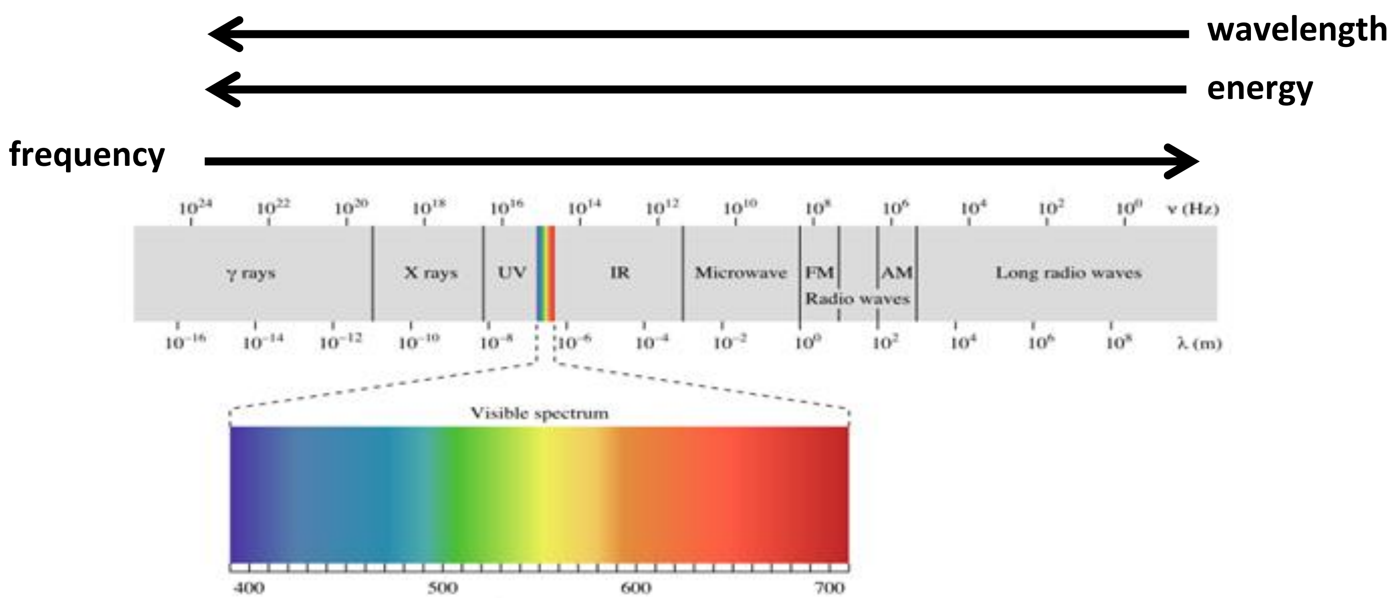
A photon is defined as a packet of light energy that has a collection of wavelengths. In physics, the energy of such a photon is defined as:

$$E = hf = \frac{hc}{\lambda}$$

where:
E = energy (J)
h = Plank's constant ($6.626 \times 10^{-34}$ J*s)
c = speed of light ($3.0 \times 10^{8}$ m/s)
λ = light wavelength (m)
f = frequency (1/s)

Sunlight is composed of various wavelengths of light that span various energy values, with ultraviolet (UV) being the highest energy and infrared (IR) being the lowest energy. The light between these two limits is the visible light range. See the electromagnetic radiation scale, below.

1. Using the energy equation above, indicate "increases" or "decreases" for each arrow.



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## Complete the following practice problems before beginning the experiment:

1. A quantum dot solution is emitting a red color with a wavelength of $700 \times 10^{-9}$ m.
   What is the energy associated with this wavelength of light?

2. You have two quantum dot solutions. Solution 1 emits a blue color of approximate wavelength $475 \times 10^{-9}$ m. Solution 2 emits a yellow color of approximate wavelength $560 \times 10^{-9}$m.
   Which solution has a larger energy and larger frequency?
   How much larger is its energy?

## Procedure

1. Record the quantum dot particle size on the worksheet.
2. Place the quantum dot solution into the holder located inside the box.
3. Turn on the black light and close the box lid.
4. Looking through the long view port, observe the quantum dot solution when exposed to black light. Record its color and associated wavelength.
5. Turn the black light off and observe the solution for 1 minute. Record your observations.
6. After all observations have been recorded, remove quantum dot solution. Trade your vial with another group so you get a different quantum dot solution.
7. Repeat steps 1-5 until you have observed and collected data for all quantum dot solutions circulating.
8. Make sure to fill in all worksheet blanks with the appropriate information.
9. Complete all worksheet questions and turn in when finished.
10. Return all quantum dot solutions to instructor and clean up activity station.

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## Data Collection and Analysis

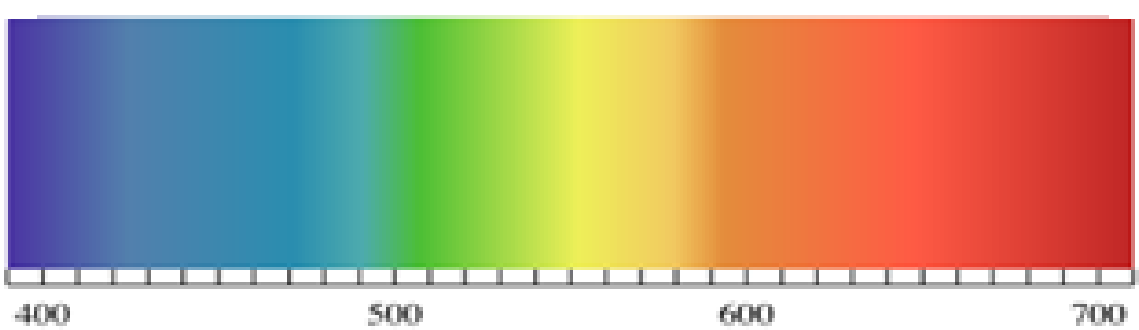
Complete the activity following the procedure steps. Make sure to record all observations.

How many quantum dot solutions are you analyzing? _______________

What type of light are you using? ______________________________________________________

| Table 1: Data Collection | | | | |
|---|---|---|---|---|
| Quantum Dot Solution # | With Exposure (light on) | Without Exposure (light off) | | Approximate Wavelength (m) |
| | Emitted Color | Emitted Color | Recorded Time until color changed | |
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |

**Visible light spectrum (1 x $10^{-9}$ m).**



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1. Using the grid below, plot the nanoparticle size-energy relationship, where wavelength is the independent variable and particle size the dependent variable.
   Label all axes, units of measure, and subdivide the graph appropriately for data collected.

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1. What is the relationship between nanoparticle size and color wavelength emitted?

2. How does the above relationship relate to energy? What is the trend of nanoparticle size and energy?

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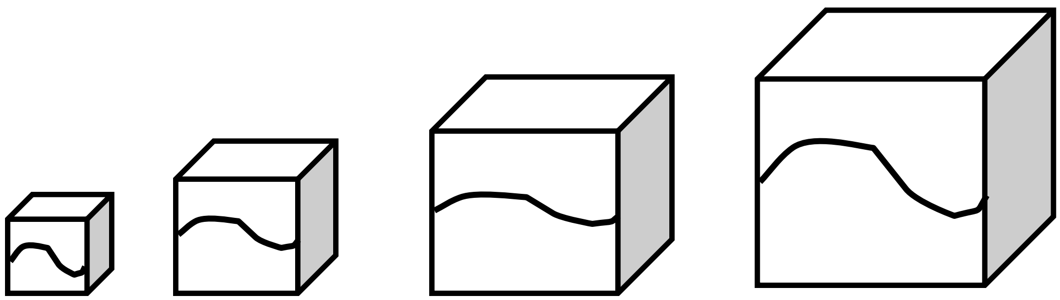
## Post-Activity Discussion Questions

1. Quantum confinement produces the nanoparticle size-energy relationship. To illustrate this concept, below are a series of boxes increasing in size, with schematic wavelengths in the boxes.
   Use this diagram to explain why higher energy light is emitted with smaller particles.
   *Hint: Look at the length of each wave and compare to each other.*



2. How might the kinetic energy of an electron change with increasing particle size?

3. Name three practical applications for quantum dots.
   Provide 1-2 sentence descriptions for each application.

4. **BONUS:** You have proven that nanoparticles emit colors with an equivalent energy proportional to the nanoparticle size. Why does this only occur in nanoparticles? Why doesn't this occur in larger materials?