## Teacher's Preparatory Guide

# *Quantum Dots Real-World Particles in a Box*

**Purpose**
The purpose of this activity is to show that nanosize particles of a given substance often exhibit different properties and behavior than macro or micro size particles of the same material. The property studied in this activity is the absorption and reflection of light which is based on energy levels that are determined by size and bonding arrangements of the materials.

**Time required:**
1 -50 minute class period for activity

**Level:**
Upper middle school to high school

**Teacher Background:**

**Nanooze:** The NNIN's online science magazine special issue Nanomedicine has a section onf "Why do quantum dots glow and what are they used for?" This makes a good accompaniment to this lesson. You can request copies at info@nanooze.org or download it at: http://www.nanooze.org/main/Nanooze/Download_Magazines.html.

**Quantum mechanics** considers matter both as particles and waves. As waves, light can diffract and interfere, and the wave behavior of electrons describes the probability of locating an electron at a particular location. But the emission of electrons when electromagnetic radiation falls on an object, called the **photoelectric effect,** shows that light also behaves like a particle.

The **electromagnetic wave theory** cannot explain the photoelectric effect because according to electromagnetic wave theory, an electric field accelerates and ejects electrons from matter and the strength of the electric field is related to the intensity of the radiation (not to the radiation's frequency). Thus, it follows that electrons in matter would need to absorb energy from a dim light source for a very long time before they gain enough energy to be ejected. But experimentation shows that this does not happen.

The electromagnetic spectrum is a group of radiations. **Radiation** is energy that travels and spreads out as it travels. Different types of radiation include radio, microwave, infrared, visible light, ultraviolet, x-rays, and gamma-rays. Electromagnetic radiation can be described in terms of a stream of photons, which are massless particles each traveling with wave-like properties and moving at the speed of light. Each **photon** contains a certain amount or **quanta** of energy, and all electromagnetic radiation consists of these photons or quanta. The only difference between the various types of electromagnetic radiation is the amount of energy found in the photons.



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The electromagnetic spectrum can be expressed in terms of energy, wavelength, or frequency. Each is related to the others in precise mathematical ways. Below is a chart that shows how these are related.

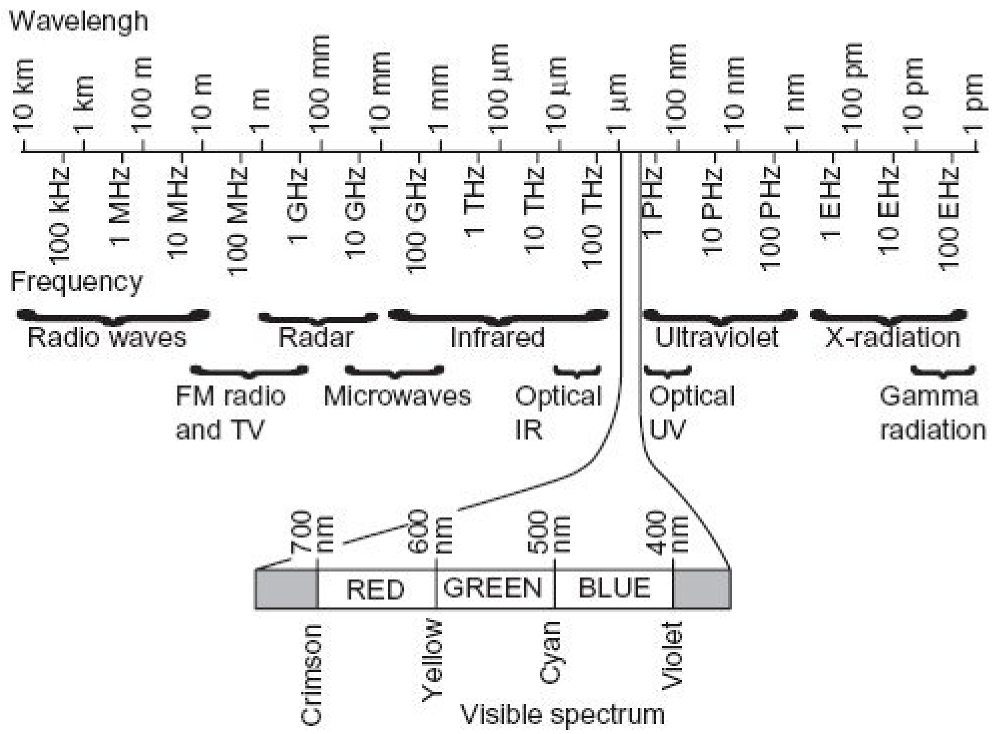


Chart 1

*http://content.answers.com/main/content/img/oxford/Oxford_Photo/0198662718.electromagnetic-spectrum.2.jpg*

From chart 1 you will notice that the longer the wavelength, the lower the frequency and the lower the energy. So, the shorter the wavelength, the higher the frequency and the greater energy of the photons.

The **visible spectrum** is the portion of the electromagnetic spectrum that is visible to the human eye. A typical human eye will respond to wavelengths from about 380 nm to 750 nm. Colors that can be produced by visible light of a single wavelength are referred to as the pure spectral colors. Although the spectrum is continuous, with no clear boundaries between one color and the next, the ranges shown in chart 2 may be used as an approximation.

**The colors of the visible light spectrum**[1]

| color | wavelength interval | frequency interval |
|---|---|---|
| red | ~ 700–635 nm | ~ 430–480 THz |
| orange | ~ 635–590 nm | ~ 480–510 THz |
| yellow | ~ 590–560 nm | ~ 510–540 THz |
| green | ~ 560–490 nm | ~ 540–610 THz |
| blue | ~ 490–450 nm | ~ 610–670 THz |
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Chart 2

So what causes the photoelectric effect? Electrons are arranged in atoms in regions around the nucleus of only certain allowable energy states called energy levels. The lowest allowable energy state of an atom is called its **ground state**. In the ground state, the atom does not radiate energy. When energy is added from an outside source ( such as visible light radiation), the electron moves to a higher energy level, and can even be emitted from the material if the energy is large enough..

The amount of radiation energy that must be absorbed to cause electrons to move energy levels is called the **threshold frequency**. No matter how intense, radiation with a frequency below the threshold frequency will not cause the ejection of electrons from energy levels. When the incident radiation's frequency is equal to or greater than the threshold frequency, increasing the intensity of the radiation causes an increase in the flow of photoelectrons.

According to Einstein, light and other forms of electromagnetic radiation consist of discrete, quantized bundles of energy, each of which was later called a photon. The energy of a photon depends on its **frequency**. Energy of a photon $E = hf$. The energy of a photon is equal to the product of Planck's constant and the frequency of the photon. E is a unit of energy commonly expressed in electron Volts eV . One electron volt is the energy of an electron accelerated across a potential difference of 1 V. A quantum is the minimum amount of energy that can be gained or lost by an atom.

When the atom is in an excited state due to an absorption of energy, the electron can drop from the higher energy level to a lower energy level. As a result of this transition, the atom emits a photon corresponding to the energy difference between the two levels. Because an atom's electron can move only from one allowable orbit to another, they can emit or absorb only certain amounts of energy. This energy can be given off as photons of light. Since only a certain amount of energy is given off, only a certain frequency of light and therefore color is radiated. This emission of light from a substance after it has absorbed energy is called **florescence**.

**Quantum dots** are small crystals 10-50 times the diameter of an atom which are small semiconductor particles that can contain one electron and one "hole" (the absence of an electron). These electrons and holes act like small particles which can move freely inside the semiconductor, but cannot get out (just like a particle in a box). By carefully observing quantum dots with different sizes, we can see the effect of changing the size of the box on the energy levels of the system.

Quantum dots are **nanoscale** semiconductors whose conducting characteristics are closely related to the size and shape of the individual crystal. Generally, the smaller the size of the crystal, the larger the band gap. The **band gap** is an energy range in a solid where no electron state exists. The band gap generally refers to the energy difference between the top of the valence band and the bottom of the conduction band which is found in insulators and semiconductors. It is the amount of energy required to free an outer shell electron from its orbit about the nucleus to become a charge carrier. As the nanocrystal size decreases, the energy of the first excited state increases, and concurrently, more energy is released when the crystal returns to its resting state. For example, in fluorescent dye applications, this equates to higher frequencies of light emitted after excitation of the dot as the crystal size grows smaller, resulting



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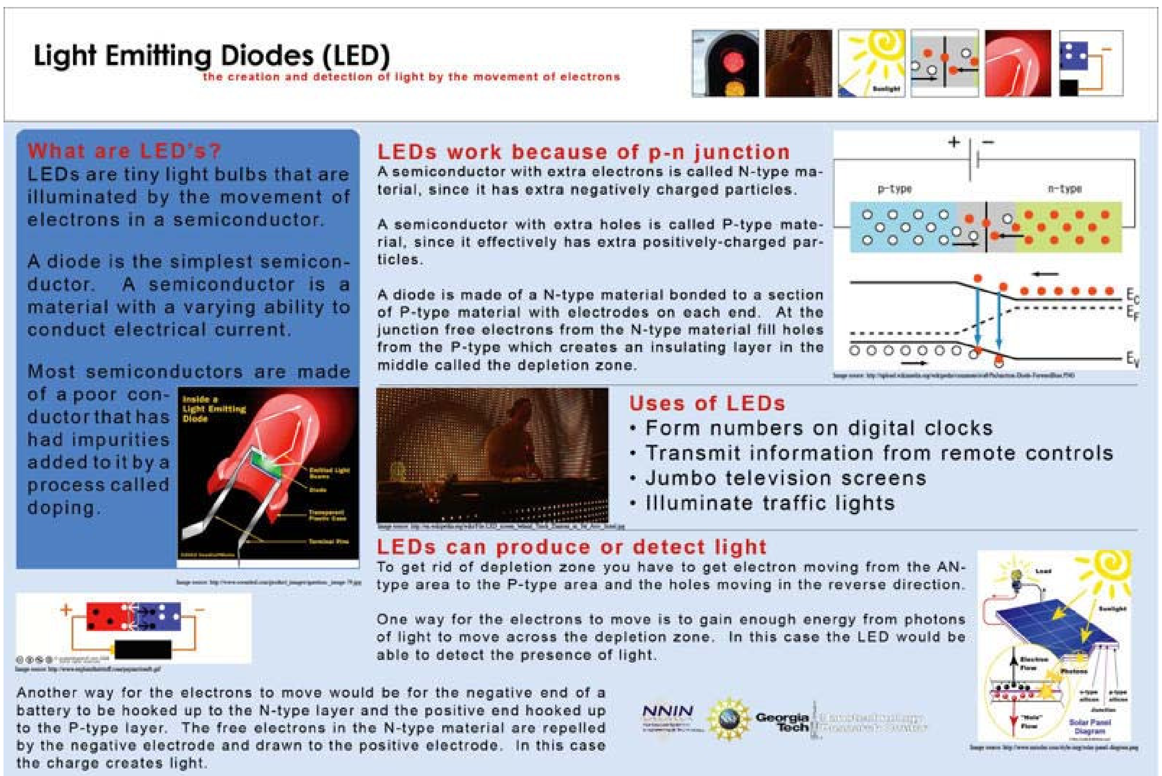
in a color shift from red to blue in the light emitted. The main advantage in using quantum dots is that because of the high level of control possible over the size of the crystals produced, it is possible to have very precise control over the conductive properties of the material

A variety of applications have been demonstrated for quantum dots and other nanocrystals, including tunable light emitting diodes (LEDs), photovoltaics, single-electron transistors, and fluorescent tags for biological imaging applications.

A **Light Emitting Diode (LED)** is a diode which only allows current (electricity) to flow in one direction and not the other. As electricity is flowing through, they also produce light. In the simplest terms, an LED is made with two different kinds of semiconductor material: one type that has too many free electrons roaming around inside, and another that doesn't have enough. When an electron from the material with too may electrons gets pushed across a thin barrier and gives up its energy in the other material, a photon or particle of light is produced . The color of light depends on a number of factors. A small bandgap that fairly weak electrons can cross gives you infrared or red light, while a large bandgap that needs really strong electron gives you light that has a blue or violet color.




**Materials**

<u>For each group of students:</u>

Set of Cenco Quantum Dots ([http://www.sargent](http://www.sargent) welch.com/quantum-particle-in-a-box-cenco/p/IG0039296/)

Set of LED Micro Lights (Yellow, Orange, Blue, White, Green, Red, Violet)

**Safety Information**



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The effects of many nano structures are not known. For that reason the glass vials containing the quantum dots, provided by Nanosys, should be left in the rack upright at all times. The vials are sealed with aluminum caps and are never meant to be opened or punctured. If they are opened , cracked or leaking please consult the MSDS sheet immediately. MSDS sheets included at the end of this lesson.

**Directions for the Activity**
1. Hand out materials and students sheets.
2. Have students read through background information on the student sheet. Answer all questions about terms or concepts before students begin activity.

## Student Activity Sheet - Worksheet with answers

# *Quantum Dots Real-World Particles in a Box*

**Essential Question:**
Will all colors of LEDs cause quantum dots to florescence? If not, why not?

**Objectives: By the end of this activity you should be able to explain:**
1. There is a positive linear relation between the energy and frequency of light.
2. Energy is gained and lost by atoms only in certain, discrete amounts.
3. The emission or absorption of light is associated with the transitions of electrons between energy levels.
4. Only certain energy levels and associated electron arrangements are allowed in atoms.

**Background Reading:**
**Quantum mechanics** considers matter both as particles and waves. As waves, light can diffract and interfere, and the wave behavior of electrons describes the probability of locating an electron at a particular location. But the emission of electrons when electromagnetic radiation falls on an object, called the **photoelectric effect,** shows that light also behaves like a particle.

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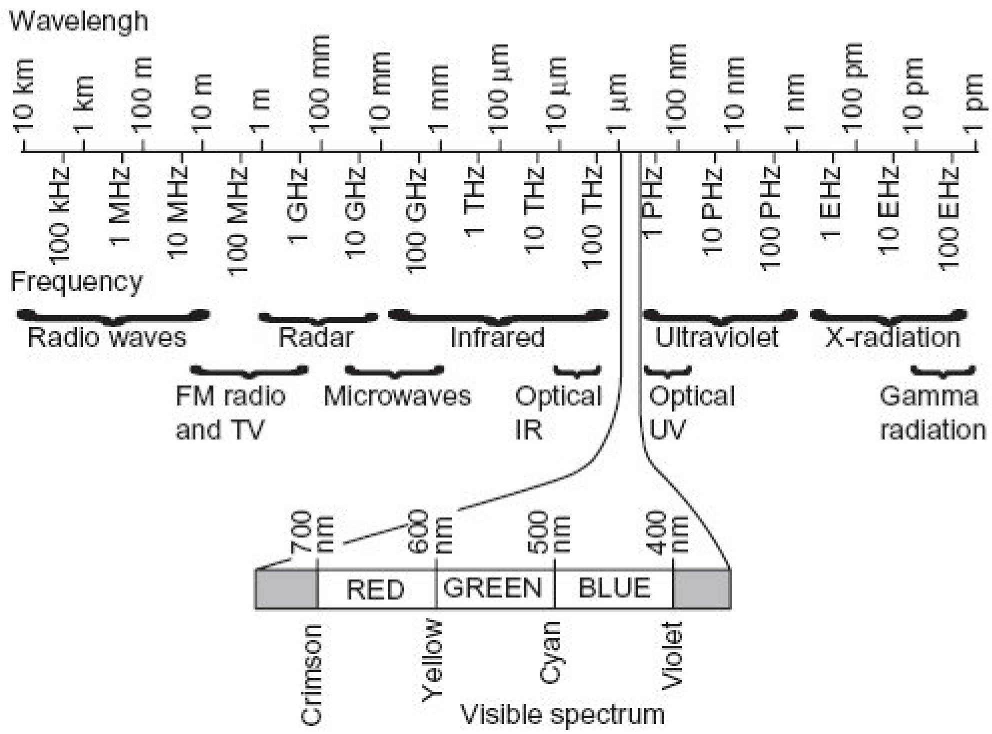


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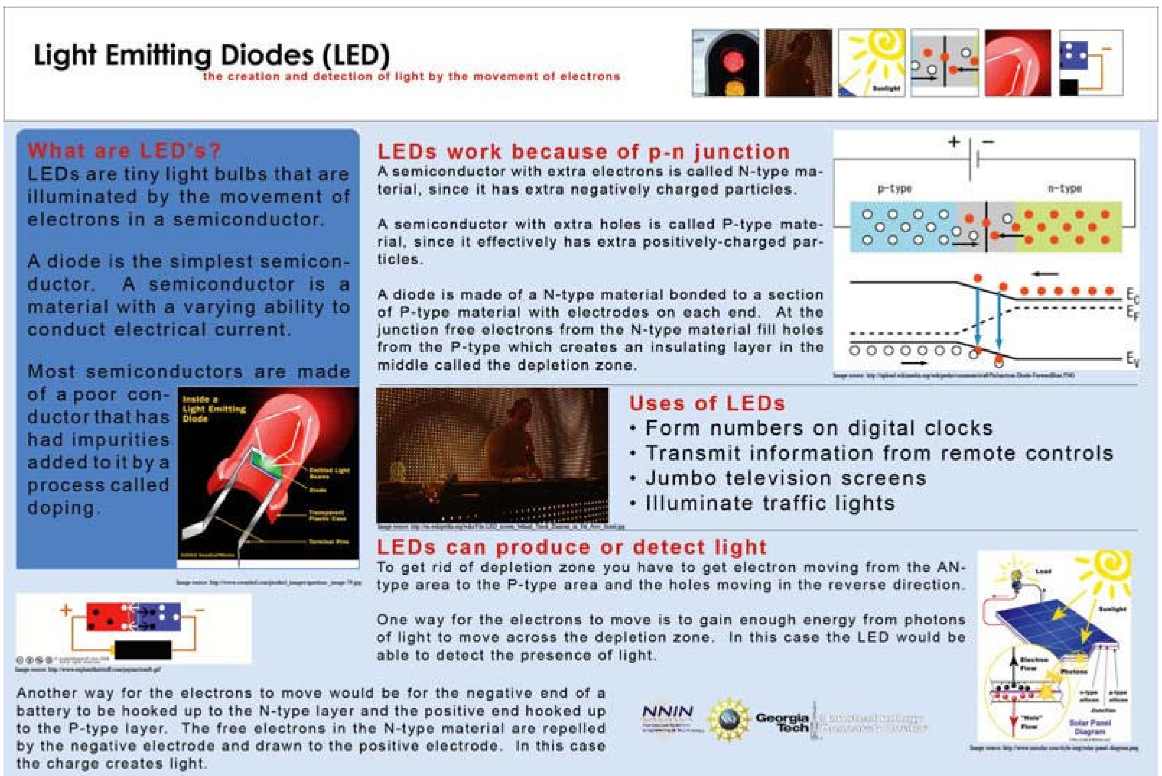





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**Procedure:**

Part 1

Question: Will a blue LED cause quantum dots to fluoresce?

Write below your answer to the question above.__( Answers will be either yes or no)

1. Take out the set of LEDs. Turn LED power on and determine the light that is emitted. List the color on the data chart 1 that follows. Continue with each of the LEDs.
2. Referring to the chart 2 in the Background Section, what would the wavelength of these colors be? Place this information in Data chart 1.

Data Table 1

| LED color | Approximate wavelength of light emitted |
|---|---|
| Yellow | 590-560 nm approximately |
| Orange | 635-590 nm approximately |
| Blue | 490-450 nm approximately |
| White | 400-700 nm approximately |
| Green | 560-490 nm approximately |
| Red | 700-635 nm approximately |
| Violet | 450-400 nm approximately |

3. Which one of these would have the least energy? How would you know?
____(Red because it has the longest wavelength and therefore would have the lowest amount of energy)________________________________________
4. Which one of these colors would have the most energy? How would you know?
____( Violet because it has the shortest wavelength and therefore would have the largest amount of energy)________________________________________

5. Look at the vials of Cenco quantum dots. These are Indium phosphide quantum dots in solution. The only difference between the vials is that the dots are different sizes.

6. Do they all appear to be the same color? If not, list the colors that they appear.
___(No, the containers appear to be green, yellow, orange and red in color)________________________________________
7. Turn the power on for the blue LED and place under each vial. Write your observations:
__( It causes the each of the vials to glow or fluoresce)________________________________________
8. What causes the containers to fluoresce? __( There has to be enough energy in the light that is shown on the particles for the electrons to move across the band gap. They would then give off the energy as light when they fall back to their ground state.)____________________________

   Do they all behave the same way? ___( Yes)________________________________
9. List which color(s) of quantum dots fluoresce.__(Green, Yellow, Orange, and Red)__________________________

Part 2

Question: Will other colors of LEDs cause the vials to fluoresce?



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Write below your answer to the question above.___( Answers will either be yes or no)________________________________

___________________________________________________________________________

1. Take each of the LEDs listed on the chart below and illuminate the bottom of each of the vials. Put an X in the column of each quantum dot that fluoresces.

| **LED Color** | **Green Quantum Dot** | **Yellow Quantum Dot** | **Orange Quantum Dot** | **Red Quantum Dot** |
|---|---|---|---|---|
| Yellow | | | | |
| Orange | | | | |
| Blue | X | X | X | X |
| White | X | X | X | X |
| Green | X | X | X | X |

2. Did all colors of LEDs caused the vials to glow? _____(No)________________________

3. What do you think makes the difference?_(Answers will vary but may include: Each color of light is a different wavelength and frequency. The longer the wavelength the smaller the amount of energy the light can radiate to the quantum dot electrons. The electrons would need enough energy to move across the band gap to be able to give off light as the electrons fall back down. Blue and green are wavelengths that are shorter and therefore have enough energy to transfer to electrons so that they were able to move and fluoresce when they fell back to their ground state. White causes them to fluoresce because it includes all wavelengths which would include blue and green.)____________________________________

Part 3

What do you think will happen if you use a red or a violet LED to illuminate the vials?
Write your answer to the question above.__(Answers will vary but may include that red will and violet will not or that violet will and red will not.)_____________________________________

1. Test your idea and write your conclusions below:
__(Students should each vial with both LEDs. They should determine that red does not cause any of the vials to glow but the violet causes all the vials to glow.)

___________________________________________________________________________

**Analysis**

1. Based on what you read in the background section, what is the relationship between the color of light and the energy of the radiation?
__(The color of light is determined by the wavelength and frequency of the radiation. The longer the wavelength and lower the frequency the lower the amount of energy in the radiation. The shorter the wavelength and higher the frequency the more energy the radiation has. So red has a longer wavelength and lower energy then violet which has a shorter wavelength and higher energy.)___________________________________________________________________________

2. Based on what you read in the background section, what is the relationship between the color of radiated light and the size of the band gap?
__( The smaller the quantum dot the larger the band gap. This means that more energy is needed to move an electron across the band gap and then more energy is radiated as color when the electron moves back to its ground state. So the larger the quantum dot the smaller the band gap. This means that less energy is needed to move an electron across the band gap and then less



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energy is radiated as color when the electron moves back to its ground state.)
___________________________________________________________________

3. Based on what you read in the background section, what is the relationship between the size of the quantum dot and the color of radiated light? _(Smaller quantum dots will radiate colors with higher energies such as violet and larger quantum dots will radiate with lower energies such as red)________________________________

**Conclusion**

1. Do your results in data charts 1 and 2 support your answers in questions 1-2 above? Why or why not?___( yes because the higher the frequency the more the energy caused the quantum dots to glow or fluoresce)____________________________________________________
___________________________________________________________________

2. Based on the data that was collected and your answers to the questions above make a guess as to the size of the particles in the vials List the vial colors from the largest particles to the smallest particles.___(Red, Orange, Yellow,
Green)_________________________________________________________________

**Assessment**

Conclusion questions will be used as an assessment tool by teacher.

**Resources:**

**To learn more about nanotechnology, here are some web sites with educational resources:**
**www.nnin.org**
**www.mirc.gatech.edu/education.php**

To locate materials and information on this lesson refer to the following:
http://nanohub.org/resources/4916 Particle Wave Duality animation
http://www.sargent welch.com/quantum-particle-in-a-box-cenco/p/IG0039296
Cenco Quantum Dots
*Using LEDs and Phosphorescent Materials to Teach High School Students Quantum Mechanics*
Journal of Chemical Education March 2009 pages 340-342
*Lesson 3 Unique Properties at the Nanoscale*
NanoSense Unit Size Matters http://nanosense.org/activities/sizematters/index.html
http://en.wikipedia.org/wiki/Visible_spectrum
http://en.wikipedia.org/wiki/Conduction_band
http://en.wikipedia.org/wiki/Valence_band

**National Science Education Standards**

Grades 9-12
Content Standard B- Interaction of energy and matter

**Georgia Performance Standards**

SC3 Students will use the modern atomic theory to explain the characteristics of atoms.
f. Relate light emission and the movement of electrons to element identification.
SP4. Students will analyze the properties and application of waves.



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a. Explain the processes that results in the production and energy transfer of electromagnetic waves.

SP6 The student will describe the corrections to Newtonian physics given by quantum mechanics and relativity when matter is very small, moving fast compared to the speed of light, or very large.



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