That's a Dot of a Different Color:

A lesson on Quantum Dots

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Content Area: Biology, Chemistry, Physics
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Grade Level: 7-12

LESSON OVERVIEW

Lesson Description

This lesson introduces quantum dots, which are semiconductor nanocrystals that have important applications in a variety of emerging fields. Quantum dots relate to topics covered in traditional science curricula, such as energy, wavelength, frequency, and biological sensing. This lesson is contextualized within a video, where students are asked to investigate important characteristics of quantum dots and compile information on quantum dots as a supporting technology for biosensors, nanomedicines, or LCDs.

Learning Goals

- Students will use a variety of data sources (TEM images, online simulation, and video) in analysis and description of relationships between quantum dot size, color, and energy. Students will graphically represent each relationship and make a statement summarizing each.
    - As quantum dot size increases, the dot goes from blue to red along the electromagnetic spectrum.
    - As the dot size increases, the energy emitted from the dot decreases.
    - As reaction time increases, the dot size becomes larger.
    - As energy increases, frequency increases.
- Students will be able to communicate their results, contextualized in an important application of quantum dot technology.

Big Ideas in Nano

- Size-dependent Properties: The properties of matter can change with scale. In particular, as the size of a material approaches the nanoscale, it often exhibits unexpected properties that lead to new functionality.
    - How this lesson relates to the big idea: The color of the quantum dot solution changes as the size of the quantum dot changes.
- Quantum Mechanics: All matter is simultaneously both a particle and a wave. At the scale at which the bulk properties of matter are important, quantum mechanics is not needed to explain the behavior of matter. As the size or mass of an object becomes smaller and approaches the nanoscale, the wave character becomes more important, and quantum mechanics becomes necessary to explain its behavior.

- How this lesson relates to the big idea: The wave properties of the quantum dot are responsible for the color of the quantum dot.

- Tools and Instrumentation: Recently developed tools allow the investigation, measurement and manipulation of matter, leading to the development of new understandings and creation of new structures. These tools drive the scientific progress in nanoscale science and technology.
  - How this lesson relates to the big idea: A TEM scan allows researchers to examine the size of the quantum dots.

Standards

- Indiana State Standards
  - Grade 7
    - 7.7.2
  - Grade 8
    - 8.3.8
  - Chemistry
    - C.1.3
    - C.1.37
  - Physics
    - P.1.11
    - P.1.29
    - P.1.31
- NSES National Standards
  - Content Standard A
  - Content Standard B
  - Content Standard E
- Benchmarks National Standards
  - 4DAM1
  - 4ESM4
  - 4ECR4
  - 4FW5
  - 8EC3

LESSON PREPARATION

Teacher Background Content Knowledge

- Quantum dots are an interesting topic because they intersect important topics in biology, chemistry, and physics. Additionally, they have important applications in electronics development, biosensors, and nanomedicines.
- Teachers should be familiar with:
  - Energy and its relationship with wavelength and frequency.
  - Atoms and energy levels
- See supplemental material for more content information.

Student Prior Knowledge Expectations

- Students should have a basic introduction to atoms and atomic orbitals. It is also helpful if students have a basic understanding of the electromagnetic spectrum.

Potential Student Alternative Ideas

- Students may have misconceptions about what energy is, and may not know that it relates to color of light. The initial exercise is intended to elicit these misconceptions and help students confront them during the lesson.
- Students will probably not have prior ideas about quantum dots, but may be confused about how size correlates with energy and color.

Potential Student Difficulties

- Students may be unfamiliar reading and interpreting actual spectroscopic data. They may also need help in finding the information they need from the TEM images and in using the online simulation.
- Students will probably not be familiar with quantum dots, and may not be familiar with some or any of the three areas of application (LCDs, nanomedicines, and biosensors).
- Students may have difficulty understanding the background reading assignments, and may have prior experience reading any kind of scientific articles. Students can search for more clarifying/simpler explanations during the preparation of their presentations, when they will be asked to consult other sources.

Materials

Item	Number/Amount
Computers with internet and Powerpoint	1 per group
Video – Quantum Dot Synthesis	1 per class

Cautions/ Potential Pitfalls

- Students may have difficulty gathering data from the online simulation. It is helpful to circulate and make sure that each group is successfully gathering data from the simulation component.

Pre-Class Preparation

Getting the Materials Ready

- Packets need to be prepared for each group with 1 set of data per group. Each student needs an "employee training" worksheet packet and a copy of their relevant literature article.

Safety Issues

- None

DOING THE LESSON

Opening

- This lesson starts with students acting as "employees" of a new company investigating the use of quantum dots in several technologies. The lesson opens with a video clip introducing the company and the three major applications that students can investigate: LCD plasma screens, nanomedicines, or biosensors. Students will select one company to work for,
- Students will write answers to the following questions in their journals or on a blank piece of paper. Students will refer to a figure of the electromagnetic spectrum.
    - What kind of information can we get from this figure?
    - Are there any important relationships that you can determine using this figure?
    - In your own words, what is energy? How do you think it is related to the information on the figure?
    - Have you ever heard of a quantum dot? What do you think a quantum dot is?

Body

- Each segment of the video will introduce a new piece of data. In between segments, students will use that data to determine 1-2 important relationships in quantum dots. These relationships will build on one another and will be tied together in the final presentation.

Activity

1. Students will watch a 10-15 min video clip showing the quantum dot synthesis.
   a. Students will be directed to observe the colors of quantum dots and how they change during the reaction.
   b. Using their observations, students will be asked to work in groups to respond to the following questions in their employee training packets.
      i. As time progresses, what pattern do you notice in the quantum dot colors?
      ii. How does this pattern relate to the electromagnetic spectrum?
      iii. Why might it be helpful to have a reaction that lets us make different colors of quantum dots in specific amounts of time (hint: it might be helpful to think about the article you read yesterday!).

2. Students will watch a 5 minute video clip, showing TEM images of the quantum dots being taken.
   a. Students will be provided with copies of the TEM images and corresponding spectroscopic data, and asked to use this data to correlate color with dot size. They can also use the online simulation to supplement this data and confirm their findings.
   b. Using their observations, students will respond to the following questions, providing a summary statement and a visual representation for each relationship.
      i. Using data from the TEM and corresponding spectroscopic data, what pattern do you see between dot size and color?
      ii. Create a graph to show the relationship between dot size and color. Hint: you can represent color using frequency!
      iii. Based on what you observed about reaction time and color, what is the relationship between dot size and reaction time? Create a graph and a summary statement for this relationship.

3. Students will watch a 5 minute video clip focusing on the relationship between size, color, and energy.
   a. The video clip with introduce the equation relating energy to frequency ($E=h\nu$) and provide a visual representation of the band gap emission phenomenon.
   b. Students will use the equation and their previous frequency data to calculate energies for each dot.
      i. Students will create a graph and a summary statement for the relationship between energy and frequency.

ii. Students will use the data from step 2 (relationship between frequency and dot size) to correlate energy to dot size, and create a claim statement and visual representation.

Wrap-up

- Students will watch the final segment of the video, where they will be introduced to their bosses. Students will be asked to prepare the final report based on their application of quantum dots and the data they have analyzed.
    - Each presentation should include a statement of each relationship and a visual representation for each.
    - Each group will address the following questions in their presentation:
        - What makes quantum dots special or unique?
        - How is your technology important to society?
        - How could quantum dots be useful for your technology?

Assessment

- Formative Assessments Table

Assessments	Where in lesson	Possible correct responses/ things to consider
Analysis of provided data	Step 2	Monitor students to help them use data to find frequencies and dot size.
Calculation of energies	Step 3	Students should accurately use frequencies and Planck's constant to determine energies.
Creation of summary statements and graphs	Steps 1, 2, 3, and wrap up	Students should create quantitative graphs for each relationship as the lesson proceeds- these build on each other and are summarized in the summative assessment section.

- The presentation is the major summative assessment for this lesson. An accurate presentation will contain a statement of the following four representations:
    - As quantum dot size increases, the dot goes from blue to red along the electromagnetic spectrum.
    - As the dot size increases, the energy emitted from the dot decreases.
    - As reaction time increases, the dot size becomes larger.
    - As energy increases, frequency increases.

ADAPTATIONS

- Extensions
    - The video also contains interviews with practicing nanoscientists that further explain the quantum dot phenomenon and discuss current research. These interviews may be particularly interesting for upper-level students, and further contextualize quantum dots within current research and applications. Supplementary information is also available on band gaps and how these relate to the color of light emitted.
- Simplifications
    - Instead of calculating energies using frequency, students can approximate the relationship that energy increases with frequency. This may be easier for students with limited math backgrounds who may not be comfortable working with exponents.

RESOURCES

- Boatman, E., Lisensky, G., and Nordell, K. (2005). A safer, easier, faster synthesis for CdSe quantum dot nanocrystals. *J. Chem. Ed.*, **82**, 1697-1699.
- http://www.rsc.org/chemistryworld/restricted/2006/July/BiosensorsMakeItBig.asp
- *http://www.sciencedaily.com/releases/2005/05/050520175142.htm*
  Science Daily — ITHACA, N.Y.
- http://www.technologyreview.com/Nanotech/16830/page1/
- Image of electromagnetic spectrum from: cache.eb.com/eb/image?id=73584&rendTypeId=35, Accessed 30 April 2008

SUPPLEMENTAL MATERIALS

Summary of Lesson

This lesson is designed for students in grades 7-12, and may be particularly appropriate for high school students studying biology, chemistry, and physics. The goal of this lesson is to help students develop an understanding of several fundamental relationships that quantum dots exhibit; for example, the relationship between energy and frequency. Many of these relationships are already covered in traditional science curricula; however, quantum dots provide an opportunity to contextualize this information in an interesting, cutting-edge nanoscale phenomenon.

The lesson is situated within an "employee training session", where students play the role of new employees at a company investigating quantum dots as a supportive technology for a variety of applications. The lesson begins with students answering questions to elicit their conceptions of energy, light, and the electromagnetic spectrum, and by introducing them to various applications. Students will choose to investigate the potential of quantum dots for LCDs, nanomedicines, or biosensors, and will work in teams to research one of these technologies.

The activity portion of the lesson occurs in segments. Video clips introduce different kinds of data that can be collected from quantum dots. After each clip, students are asked to analyze some portion of data for a specific relationship, and create a claim statement and a visual representation for each relationship. Specifically, they will investigate the relationships between energy and frequency, dot size and reaction time, dot size and dot color (expressed as frequency), and dot size and energy.

Once students have analyzed their data, they will search for articles relating to their quantum dot application, and will prepare a presentation for their "bosses". This presentation will present their data analysis, explain how quantum dots are used as a supportive technology for their application, and explain why their application is important or beneficial. The presentation is the major summative assessment in this lesson.

Standards

Indiana State Standards

- Grade 7
    - 7.7.2: Use different models to represent the same thing, noting that the kind of model and its complexity should depend on its purpose.
- Grade 8
    - 8.3.8: Explain that all matter is made up of atoms which are far too small to see directly through an optical microscope. Understand that the atoms of any element are similar but are different from atoms of other elements. Further understand that atoms may stick together in well-defined molecules or may be packed together in large arrays. Also understand that different arrangements of atoms into groups comprise all substances.
- Chemistry
    - C.1.3: Recognize indicators of chemical changes such as temperature change, the production of a gas, the production of a precipitate, or a color change.
    - C.1.37: Describe that spectral lines are the result of transitions of electrons between energy levels and that these lines corresponds to photons with a frequency related to the energy spacing between levels by using Planck's relationship ($E=hv$).
- Physics
    - P.1.11: Recognize energy in its different manifestations, such as kinetic, gravitational potential, thermal, chemical, nuclear, electromagnetic, or mechanical.
    - P.1.29: Describe the nuclear model of the atom in terms of mass and spatial relationships of the electrons, protons, and neutrons.
    - P.1.31: Explain the role of the strong nuclear force in binding matter together.

NSES National Standards

- Content Standard A: As a result of activities in grades 5-8, all students should develop
    - Abilities necessary to do scientific inquiry.
    - Understandings about scientific inquiry.
- Content Standard B: As a result of their activities in grades 5-8, all students should develop an understanding of
    - Properties and changes of properties in matter.
    - Transfer of energy.

- Content Standard E: As a result of activities in grades 5-8, all students should develop
    - Abilities of technological design.
    - Understandings about science and technology.
- Content Standard A: As a result of activities in grades 9-12, all students should develop
    - Abilities necessary to do scientific inquiry.
    - Understandings about scientific inquiry.
- Content Standard B: As a result of their activities in grades 9-12, all students should develop an understanding of
    - Structure of atoms.
    - Structure and properties of matter.
    - Chemical reactions.
    - Interactions of energy and matter.
- Content Standard E: As a result of activities in grades 9-12, all students should develop
    - Abilities of technological design.
    - Understandings about science and technology.

Benchmarks National Standards

- 4DAM1: An atom's electron configuration, particularly the outermost electrons, determines how the atom can interact with other atoms. Atoms form bonds to other atoms by transferring or sharing electrons.
- 4ESM4: Energy appears in different forms. Heat energy is in the disorderly motion of molecules. Arrangements of atoms have chemical energy.
- 4ECR4: Different energy levels are associated with different configurations of atoms in molecules. Some changes of configurations require a net input of energy, whereas others cause a net release.
- 4FW5: Human eyes respond to only a narrow range of wavelengths of electromagnetic waves-visible light. Differences of wavelength within that range are perceived as differences of color.
- 8EC3: Miniaturization of information processing hardware can increase processing speed and portability, reduce energy use, and lower cost. Miniaturization is made possible through higher-purity materials and more precise fabrication technology.

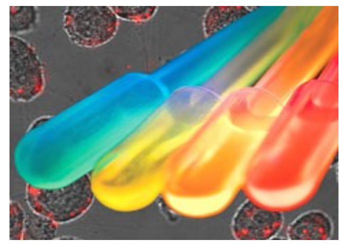
Literature Excerpt: "Biosensors make it big"
July 2006
http://www.rsc.org/chemistryworld/restricted/2006/July/BiosensorsMakeItBig.asp

Quantum promise

Other researchers have investigated attaching biological particles such as proteins and antibodies to carbon nanotubes and monitoring their electrical conductivity rather than their fluorescence. But carbon nanotubes aren't the only nanoparticles that are being developed as biosensors. Many researchers are equally excited about quantum dots.

These are semiconductor nanocrystals, often made from silicon or cadmium compounds that can fluoresce at wavelengths that span the visible spectrum, depending on their precise size. Biosensor researchers are using them in a similar manner to carbon nanotubes, by linking their fluorescence to an attached biomolecule.

For instance, researchers from Johns Hopkins University, Baltimore, US, led by biomedical engineer Jeff Tza-Huei Wang, have used quantum dots to detect specific DNA strands.



New biosensors make the most of quantum dot fluorescence
© Rebeka Drezel, Rice University, US

The researchers attach a fluorescent compound known as Cy5 to a DNA probe and the protein biotin to another. They then add these probes to a sample containing the target DNA strand and quantum dots coated with the protein streptavidin, which naturally binds to biotin.

The two probes bind to the target strand and then attach themselves to a quantum dot, via the binding between biotin and streptavidin. The quantum dot and Cy5 are now in such close proximity that, when illuminated with a laser, the quantum dot transfers its fluorescence to Cy5 through a process known as fluorescence resonance energy transfer. This generates a characteristic fluorescence signal that can easily be detected.

Bioengineer Rebekah Drezek and her colleagues at Rice University, Houston, US, have adopted a slightly different approach. They have linked quantum dots to gold nanoparticles via a short peptide sequence, which causes the gold nanoparticles to inhibit the quantum dots' fluorescence. These nanoparticle conjugates can now detect any proteases (protein-digesting enzymes) that are able to cleave the peptide linker and release the quantum dots, allowing them to fluoresce freely.

Using different peptide linkers, Drezek hopes to develop biosensors that can detect a whole range of proteases. 'This is important not only for early detection of several diseases, but, perhaps more significantly, in understanding and monitoring the efficacy of therapeutic interventions, including the growing class of drugs that act as protease inhibitors,' she says.

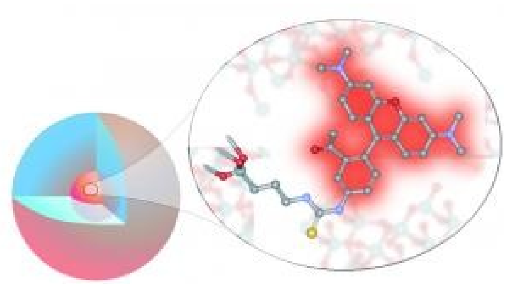
Scientists are attaching similar biomolecules to a wide range of materials, in order to assess their potential as sensing elements. For instance, Pishko has embedded a range of enzymes, such as acetylcholinesterase, into the hydrogel poly(ethylene glycol) and used it to detect compounds that react with those enzymes, including inhibitors. These reactions cause the pH of the hydrogel to change and this alters the fluorescence of a compound incorporated into the hydrogel.

Literature Excerpt: After Quantum Dots, Now Come Glowing 'Cornell Dots,' For Biological Tagging, Imaging And Optical Computing

http://www.sciencedaily.com/releases/2005/05/050520175142.htm
Science Daily — ITHACA, N.Y.

By surrounding fluorescent dyes with a protective silica shell, Cornell University researchers have created fluorescent nanoparticles with possible applications in displays, biological imaging, optical computing, sensors and microarrays such as DNA chips. These are all applications for which quantum dots have been used or are being considered. But the new Cornell nanoparticles offer an appealing alternative because of their greater chemical inertness and reduced cost.

"People have done superb experiments with quantum dots that were not previously possible," says Ulrich Wiesner, Cornell associate professor of materials science and engineering. "Hopefully Cornell dots will serve the same purpose and offer new possibilities." There are also some interesting physics questions about how the new dots work, he adds.


Schematic representation of a Cornell Dot, with several molecules of a fluorescent rhodamine dye encapsulated in the center. The dye has been modified with a group that links to the encapsulating silicon.

Since optical microscopes can't resolve individual molecules, and electron microscopes can't be used on living organisms, biologists often tag organic molecules with fluorescent dyes in order to track their movements through biological processes, such as the action of enzymes inside a living cell. While it can't see the molecules, an optical microscope can track the bright light given off by the dye.

Quantum dots -- which have been used for the same purpose -- are tiny particles of semiconductors such as cadmium selenide that behave as if they were individual atoms: They can absorb light energy, kicking their internal electrons up to higher energy levels, then release the energy by emitting light. A quantum dot fluoresces much more brightly than a dye molecule, making it a desirable marker.

Cornell dots, also known as CU dots, are nanoparticles consisting of a core about 2.2 nanometers (nm) in diameter containing several dye molecules, surrounded by a protective silica shell, making the entire particle about 25 nm in diameter. The researchers call this a "core-shell architecture." (A nanometer is one-billionth of a meter, about three times the diameter of a silicon atom.)

Like quantum dots, CU dots are many times brighter (20-30 times) than single dye molecules in solution and resist "photobleaching," a process by which dyes in solution rapidly lose their fluorescence. CU dots can be made with a wide variety of dyes, producing a large assortment of colors.

The manufacture of CU dots and early experiments with them are described in a paper, "Bright and Stable Core-Shell Fluorescent Silica Nanoparticles," in the journal Nano Letters (Vol. 5, No. 1) by Wiesner and his Cornell colleagues Hooisweng Ow, Daniel R. Larson, Mamta Srivastava, Barbara A. Baird and Watt W. Webb.

Unlike quantum dots, CU dots are mostly chemically inert. The silica shell is silicon dioxide -- essentially glass. For use as biological markers, quantum dots are encased in a polymer shell -- a process that adds to their already high manufacturing cost. Quantum dots also contain heavy metals like cadmium that can leach through the polymer shell and disrupt the chemistry being observed.

However, Wiesner says, "Silica is benign, cheap and easy to attach, and it is totally compatible with silicon manufacturing technology. That opens enormous possibilities in the life sciences and in information technology."

The Cornell researchers tested the use of CU dots as biological markers by attaching an antibody, immunoglobin E (IgE), and observing how this combination attached to cell receptors on leukemia mast cells.

The dots also offer an intriguing physics question: Why do they fluoresce so brightly? In effect, the whole is brighter than the sum of its parts. "We have this enormous brightness, and we don't know exactly where it's coming from," Wiesner says. Several explanations have been offered. One is that the silicon shell protects the dye molecules from the solvent. A second is that dye molecules floating free can lose energy by actions other than emitting photons, but in the packed core of the particle those other actions are diminished.

The dots were created by Ow, then Wiesner's graduate student. Webb, the S.B. Eckert Professor in Engineering, and Larson, a graduate student in applied and engineering physics now at Albert Einstein College of Medicine, studied their photophysical properties. Baird, director of the Cornell Nanobiotechnology Center, and Srivastava, a postdoctoral researcher, studied the dots as labels on living cells.

Literature Excerpt: Nanocrystal Displays

http://www.technologyreview.com/Nanotech/16830/page1/

Seth Coe-Sullivan, chief technology officer at Watertown, MA, startup QD Vision, fastens alligator clips to two edges of a transparent wafer the size of a cell-phone screen and flips a switch: a rectangle filling the center of the wafer suddenly turns from reflective silver to faint red. A lab worker turns off the room lights to heighten the effect -- but this isn't necessary. Coe-Sullivan turns a knob and the device begins glowing brilliantly. [For images of this research, the team, equipment, and prototypes, click here.]

This is QD Vision's first display -- a monochromatic 32-by-64-pixel test bed for a technology Coe-Sullivan hopes will replace those used in today's high-definition TVs. Thin and flexible, the next-generation display will be easy to see in sunlight and less power hungry than the one in your current laptop, he says. It will also cover more of the visible color spectrum than current displays and produce such high-contrast images that today's flat-screen displays will look dull and washed out by comparison.

At its heart are nanoparticles called quantum dots, nanoscale semiconductor crystals. By altering the size of the particles, researchers can change the color they emit.

Where these particles really shine is in the purity of the colors they emit. Displays create millions of colors from a palette of just three: each pixel is made of a red, a green, and a blue subpixel, and varying their relative intensities varies the pixel's apparent color. In LCDs and organic light-emitting devices (OLEDs), a new kind of display, the subpixel colors are impure. The red, for example, while made mostly of red light, also contains smaller amounts of other colors. With quantum dots, however, the red subpixel emits only red.

This purity means quantum dot-based displays have more-saturated color than LCDs, OLEDs, and even bulky cathode-ray tubes (CRTs), which are still prized for their excellent color rendition. What's more, Coe-Sullivan says, the range of colors possible in a quantum dot display is 30 percent greater than in CRTs: "We're increasing the depth of the green that screens can display, and the depth of the blue-green, et cetera. It's actually a different color than can be seen on an LCD, OLED, or CRT."

Perhaps what is most exciting about quantum dot LEDs (QD-LEDs) is that they use much less power than LCDs. In LCDs, a backlight illuminates every pixel on the screen. Dark pixels are simply blocking this light, in effect wasting energy. In part because quantum dots emit light rather than filtering it, a QD-LED display could potentially use one-30th the power of an LCD.

And there's another benefit to not having a backlight, according to Vladimir Bulovic, an expert at MIT in OLED displays. Because in LCDs the dark pixels don't block light perfectly, Bulovic says, the "black" pixels on LCDs are really just dark grey. With quantum dots, on the other hand, black pixels emit no light. "What makes the picture crisp and really jump out at you is that the black is really, really dark," he says.

"Beakers of This Glowing Green Stuff"

The idea to use quantum dots in displays is not new. In the early 1990s, when chemists such as Moungi Bawendi, now an MIT professor of chemistry and scientific advisor at QD Vision, were perfecting techniques for forming precise, uniform quantum dots, some tried to make QD-LEDs but produced only dim, inefficient devices that required about a

hundred thousand electrons to coax quantum dots to emit a single photon. In contrast, Coe-Sullivan's QD-LEDs require only about 50 electrons per photon.
Achieving this advance required the right people to come together at the right time. That happened in 2000, when Coe-Sullivan came to MIT as a graduate student and met Bawendi and a brand new MIT electrical-engineering professor who had arrived a few weeks before -- Vladimir Bulovic.

Just inside the door to QD Vision's lab is a row of flasks containing a bubbling red liquid -- a solution of recently formed quantum dots. The collaboration that led to the first efficient QD-LED display began after Bulovic, on a visit to MIT, stumbled upon a similar scene in the lab of one of Bawendi's collaborators.

Bulovic says that before he encountered "beakers of this glowing green stuff" at MIT, he had "never heard of quantum dots." Coe-Sullivan borrowed Bulovic's knowledge of OLED fabrication tricks and Bawendi's quantum dot expertise and also enlisted the help of fellow students Jonathan Steckel and Wing-Keung Woo.

Even with all this expertise, however, the breakthrough that enabled the device occurred partly by accident. The researchers had mixed quantum dots into a solution of organic molecules and spread the mixture into a thin film using a process called spin-casting, in the hope that the quantum dots would disperse evenly through the film. As it turned out, the quantum dots rose to the surface of the film and assembled in an orderly, uniform layer just one dot thick, an arrangement that turned out to be more efficient than the one the researchers had intended.

This layer of quantum dots became the core of a multilayer single-color QD-LED, sandwiched between electrodes and charge transport layers. Coe-Sullivan, along with Bulovic and Greg Moeller, director of business development, founded QD Vision in 2004 to move from this simple device to a full-color display that can be profitably manufactured.

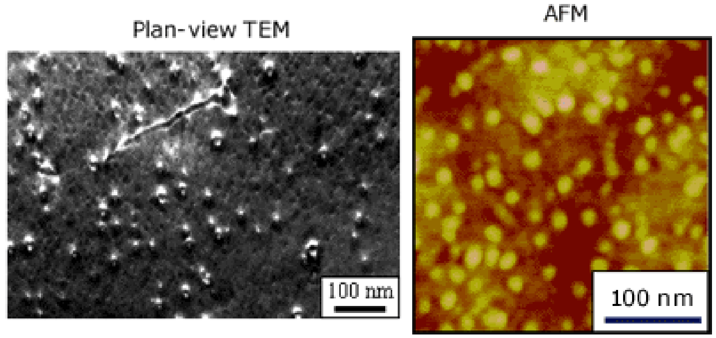
A major step was arranging arrays of pixels. At QD Vision, Coe-Sullivan points to a glass-front cabinet carefully blocked off to hide part of a proprietary process for distributing quantum dots in the alternating three-color rectangular grids necessary for a working display. Already the technique, which Coe-Sullivan says should lead to relatively inexpensive manufacturing, has produced patterns with pixels smaller than those typical of current displays.

Coe-Sullivan says QD Vision should be able to borrow from OLED technology one key component of displays, the "back plane" that controls the pixels. Now the company is focused on improving the efficiency of its device, which, while competitive with cell-phone displays, could still be improved.

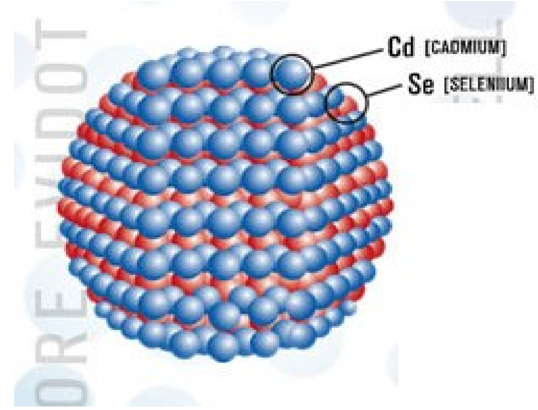
In all, Coe-Sullivan says he expects that it will be about four years before the company has its first commercial product -- probably a small display for a cell phone. But he says the colorful images will be worth the wait.

Quantum Dot Images and Models

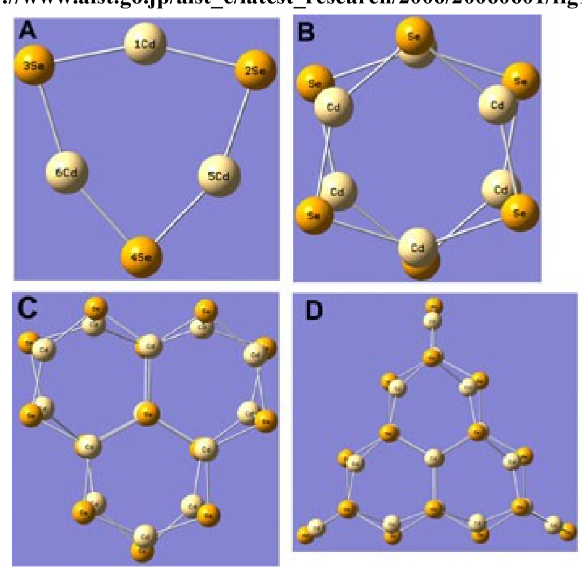
Microscopy Images
http://www.physics.ucsb.edu/~awschalom/research/images/cdse.gif



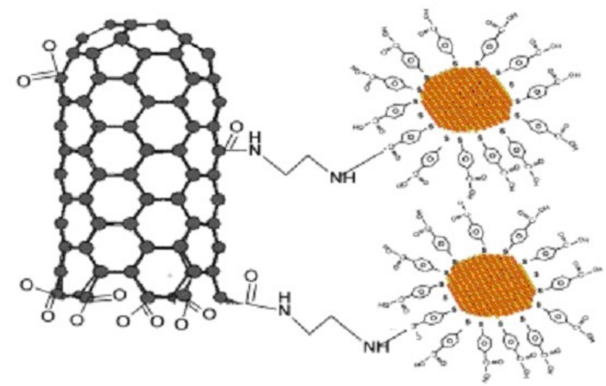
Quantum Dot Model
http://www2a.cdc.gov/niosh-nil/uploads01/evident_cadmium_1_tn.jpg



The Building Blocks of Quantum Dots
http://www.aist.go.jp/aist_e/latest_research/2006/20060601/fig1.jpg



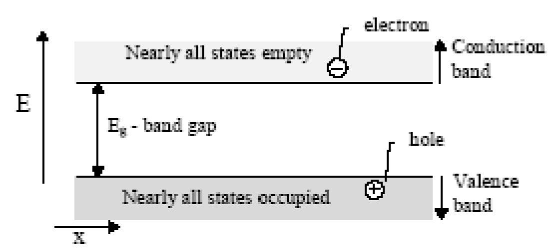
Functionalized Quantum Dots
www.sunysb.edu/chemistry/faculty/swong.htm



Energy Levels Overview

Electrons in materials can only have certain allowable energies, or energy levels, and can only exist at an energy level and not in between them. An electron with a different energy than another electron is described as being in a different energy level, and quantum mechanics states that only two electrons can fit in any given level. In addition, there exist regions where electrons cannot exist a certain energy levels, known as the bandgap, electrons occupying energy levels below the bandgap are described as being in the valance band. Electrons occupying energy levels above the bandgap are known as being in the conduction band. Due to the Pauli Exclusion Principle, electrons will start filling the lowest energy levels first, and continue to fill levels with higher energies until no more electrons remain.

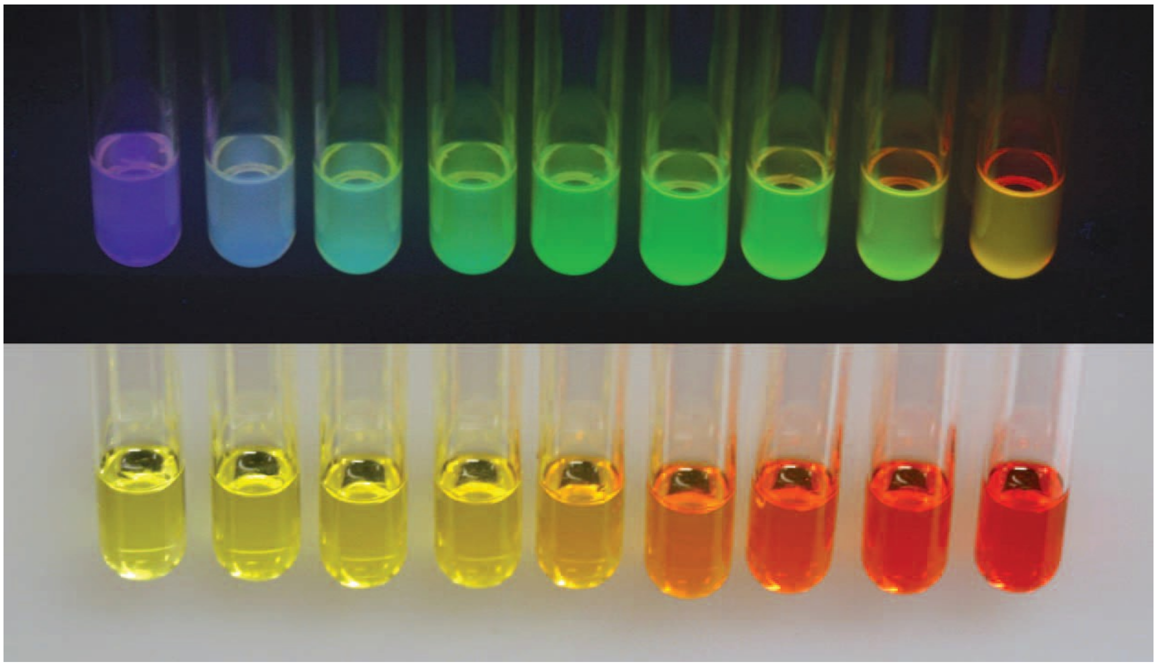
In a quantum dot, a special case of semiconductor, the allowed energy levels are arranged into bands with a gap in electron energy separating the highest energy band full of electrons from the lowest energy band empty of electrons. These bands are termed the valence and conduction bands respectively. When such material is excited, either thermally or by photons of sufficient energy, electrons are promoted from the full valance band into the conduction band. Note: the only way for an electron in the valance band to jump into the conduction band is to acquire energy. This process leaves a ‘hole’, that is an allowed energy level in the valance band which is not now occupied by an electron, and also an electron in the conduction band. The hole, which represents the absence of an electron in an otherwise full or nearly full band can be thought of as a positively charged particle similar to an electron but with opposite sign charge (see figure below). Both the hole in the valance band and the electron in the conduction band are free to move.



If an electron in the conduction band subsequently comes to the same position in the crystal as a hole in the valance band, recombination can take place. This is a process whereby the electron ‘falls’ into the hole and annihilates it (the pair of the electron and the hole is known as an exciton, which has a natural physical separation, the exciton Bohr radius). That is to say the electron makes the transition from the conduction band to the empty state in the valance band and liberates the energy difference between the two states. This energy may be given off in the form of a photon which will have an energy equal to the difference between the two states, which for an electron close to the bottom of the conduction band and a hole close to the top of the valance band will be approximately equal to the band gap energy. Thus, when an electron and a hole meet they may recombine and a photon may be emitted, the energy of the photon depending on the energy difference between the two states, thus fixed emission frequencies.

Quantum dots offer the ability to tune the bandgap and hence the emission wavelength. This is due to the small and finite separation between energy levels (also known as quantum confinement) which implies that the addition or subtraction of just a few atoms to the quantum dot has the effect of altering the boundaries of the bandgap. Changing the geometry of the surface of a quantum dot also changes the bandgap energy. Thus, with quantum dots, the size of the bandgap is controlled simply by adjusting the size of the dot. Since the emission frequency of a dot is dependent on the bandgap, it is possible to control the output wavelength of a dot, or its color.

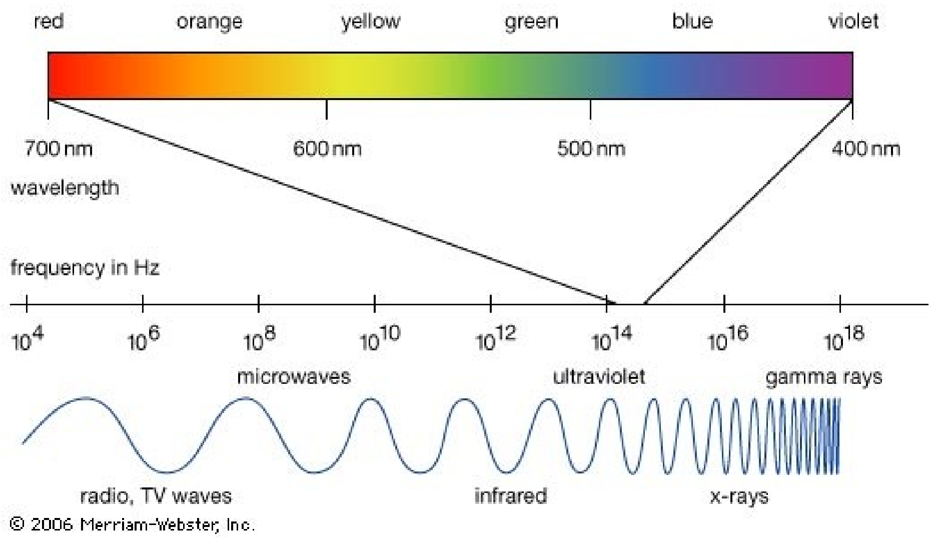
Quantum dots fluoresce under UV light. Here is an image of the dots we have pictured later both under fluorescence and not.



Boatman, Lisensky & Nordell (2005)

QUANTUM DOT CREATIONS- EMPLOYEE TRAINING PACKET

Welcome to Quantum Dot Creations! As a new employee, you will be investigating quantum dots, which have important applications in a lot of areas here at QDC! Before we start, we want to know some of your ideas that you already have about important quantum dot topics. Don't worry about accuracy- we just want to know what you think!



1. What kind of information can we get from this figure?

2. Are there any important relationships that you can determine using this figure?

3. In your own words, what is energy? How do you think it is related to the information on the figure?

4. Have you ever heard of a quantum dot? What do you think a quantum dot is?

I. Synthesis analysis

Hi QDC employees! Now that you've seen the synthesis, you're going to need to use your observations to make your first claim about quantum dots! Make sure that every time you discover a new relationship, you write a summary statement of that relationship and create a graph to show it visually.

1. As time progresses, what pattern do you notice in the quantum dot colors?

2. How does this pattern relate to the electromagnetic spectrum?

3. Why might it be helpful to have a reaction that lets us make different colors of quantum dots in specific amounts of time (hint: it might be helpful to think about the article you read yesterday!).

II. Interpreting images

Now you've got some real data to work with! You have two important relationships here, so make sure to write your summary statement and make graphs for each one.

1. Using data from the TEM and corresponding spectroscopic data, what pattern do you see between dot size and color?

2. Create a graph to show the relationship between dot size and color. Hint: you can represent color using frequency!

3. Based on what you observed about reaction time and color, what is the relationship between dot size and reaction time? Create a graph and a summary statement for this relationship.

III. Size and Energy

Hi QDC employees! Now it's time to dive into some calculations. Remember, ν is Planck's constant, and is equal to 6.626 x 10^{-34} m^2*kg/s.

1. Using E=hν, calculate the energies associated with each quantum dot color.

2. Create a graph to show the relationship between energy and frequency. Summarize the relationship in a short statement.

3. Based on what you know about the relationships between energy and frequency, and frequency and dot size, what is the relationship between energy and dot size? Create a graph and a summary statement for this relationship.

IV. Presentation

It's time for your final presentation to your bosses. Your presentation needs to have all of the following components so that your bosses can get the full picture of how quantum dots can be used for your application. Good luck!

1. You should have a summary statement and evidence (example: graphical representation) for each of the following relationships:

   Reaction time and color

   Reaction time and size

   Frequency and size

   Energy and frequency

   Energy and size

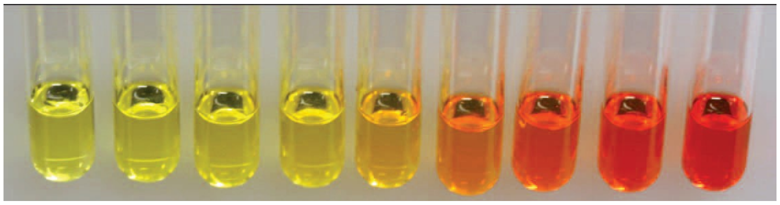
2. What makes quantum dots special or unique?

3. How is your technology important to society?

4. How could quantum dots be useful for your technology?

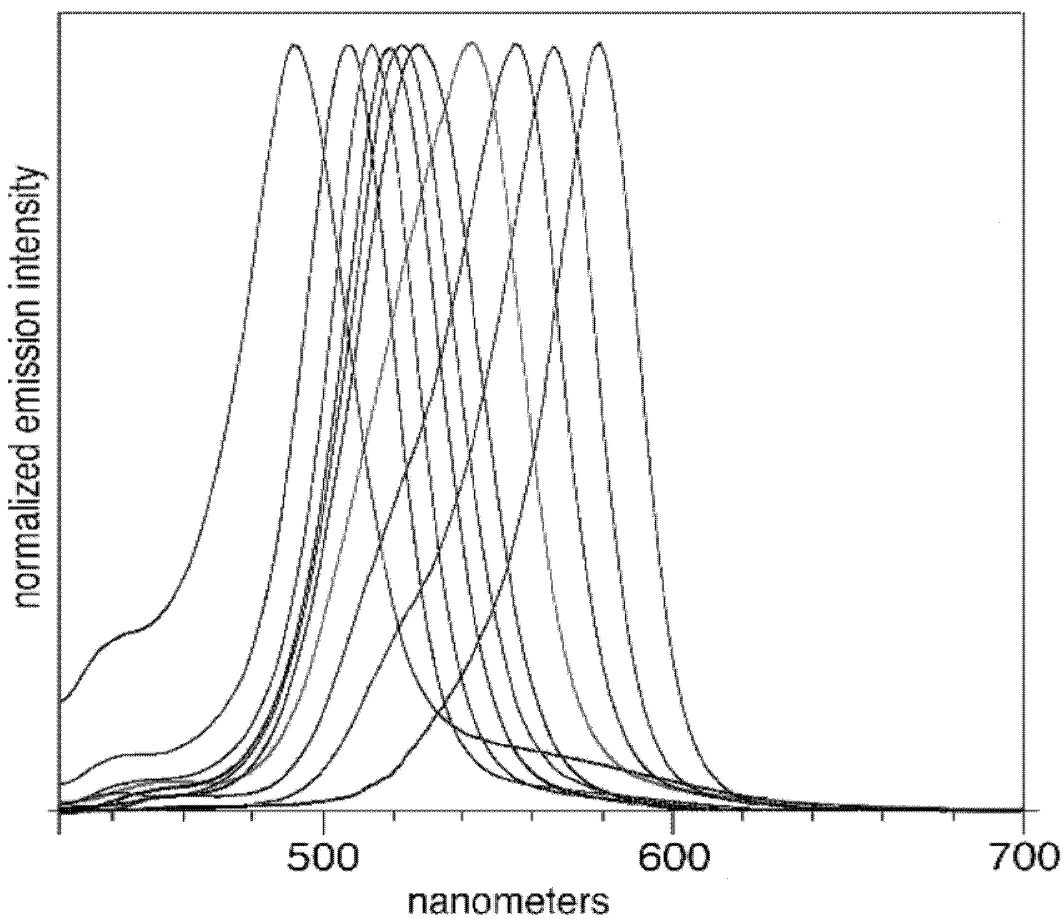
Data Sheet #1 (Post-synthesis data)

(Data from Boatman et al., 2005)



First removal ⇒ ⇒ ⇒ ⇒ Last removal

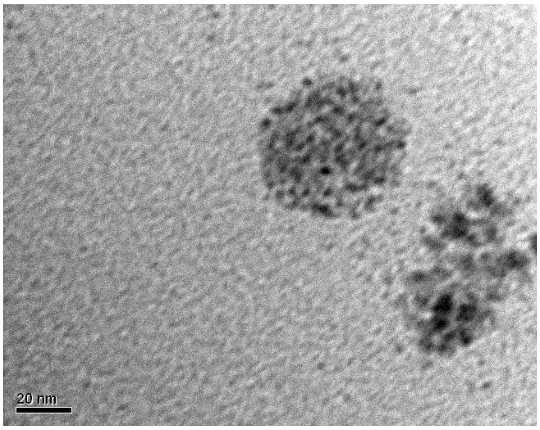
Sample	1	2	3	4	5	6	7	8	9	10
Removal Time (seconds)	8	16	24	32	40	50	65	85	110	140

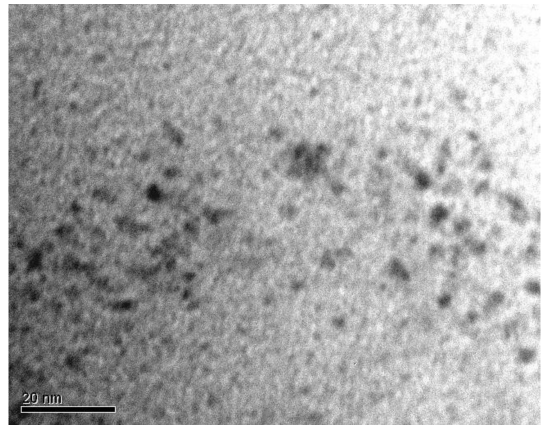


(Hint: Emission is represented here in wavelength. To convert to frequency, you will need the following equation: $\nu = \frac{c}{\lambda}$)

Data Sheet 2 (TEM images)

These are examples of transmission electron microscope (TEM) images taken of our quantum dots:





The images are a little hard to measure, so we have data for all of our samples for you to analyze and determine relationships between color, energy, and dot size.

Sample	1	2	3	4	5	6	7	8	9	10
Dot size (nm)	1.8	1.9	2.1	2.3	2.6	2.8	3.1	3.3	3.7	4.0