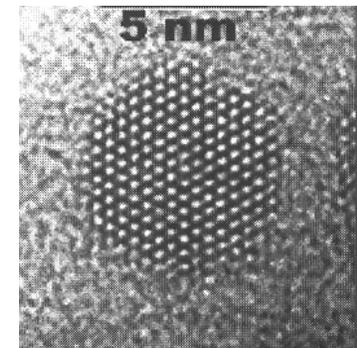
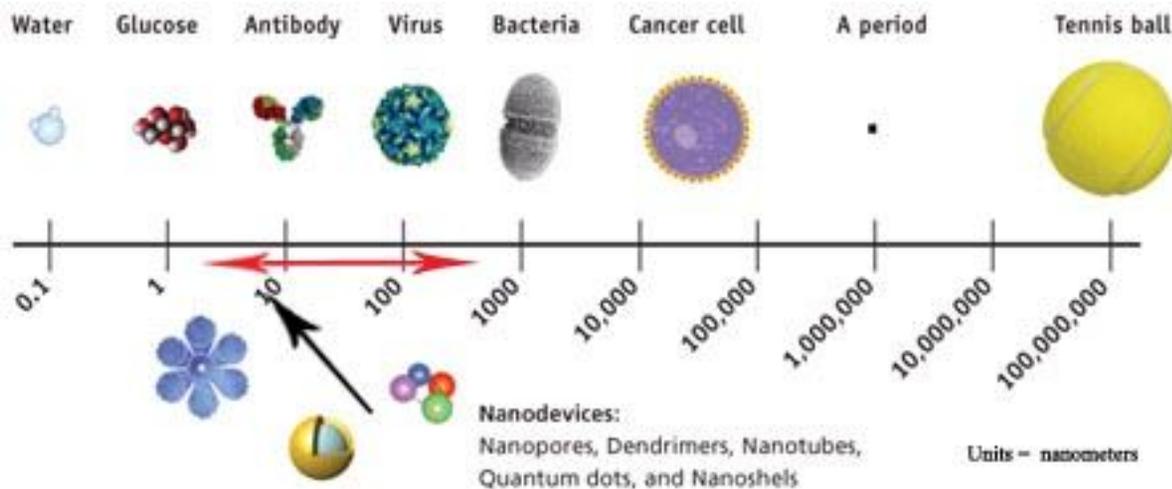
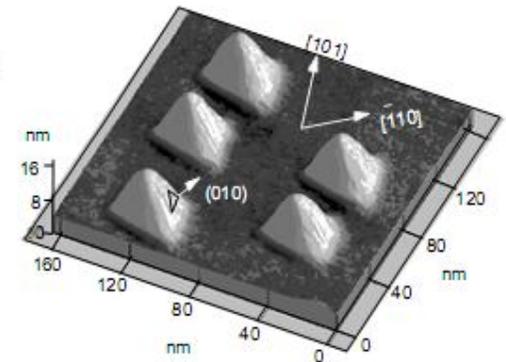


Quantum Dots

Quantum dots are extremely small semiconductor structures, usually ranging from 2-10 nanometers (10-50 atoms) in diameter. At these small sizes materials behave differently, giving quantum dots unprecedented tunability and enabling never before seen applications to science and technology.



PbSe/PbTe
(111) dots



Quantum Dots

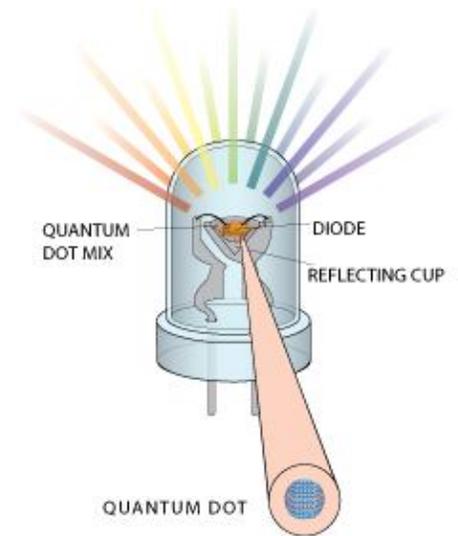
Quantum dots may some day light your homes, offices, streets, and entire cities.

Quantum dot LED's can now produce any color of light, including white.

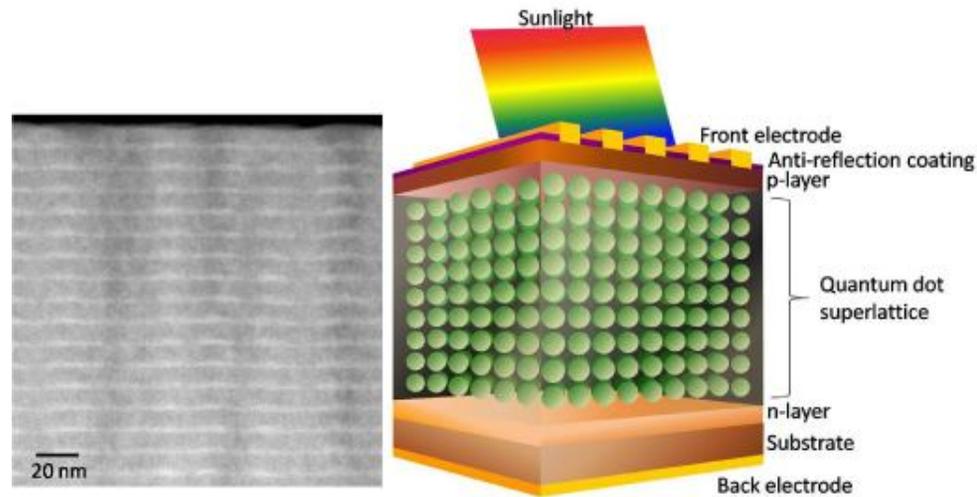
Quantum dot LED's are extremely energy efficient. They use only a few watts, while a regular incandescent lamp uses 30 or more watts for the same amount of light.

You've already seen quantum dot LED's in action. Many traffic lights in the Buffalo area use them.

Although these LED's use less energy and last much longer than a regular bulb (according to the U.S. Department of Energy, LEDs last 25 times as long as incandescent bulbs), they're still much more expensive, although this has changed recently as mass production has become possible.



Quantum Dots



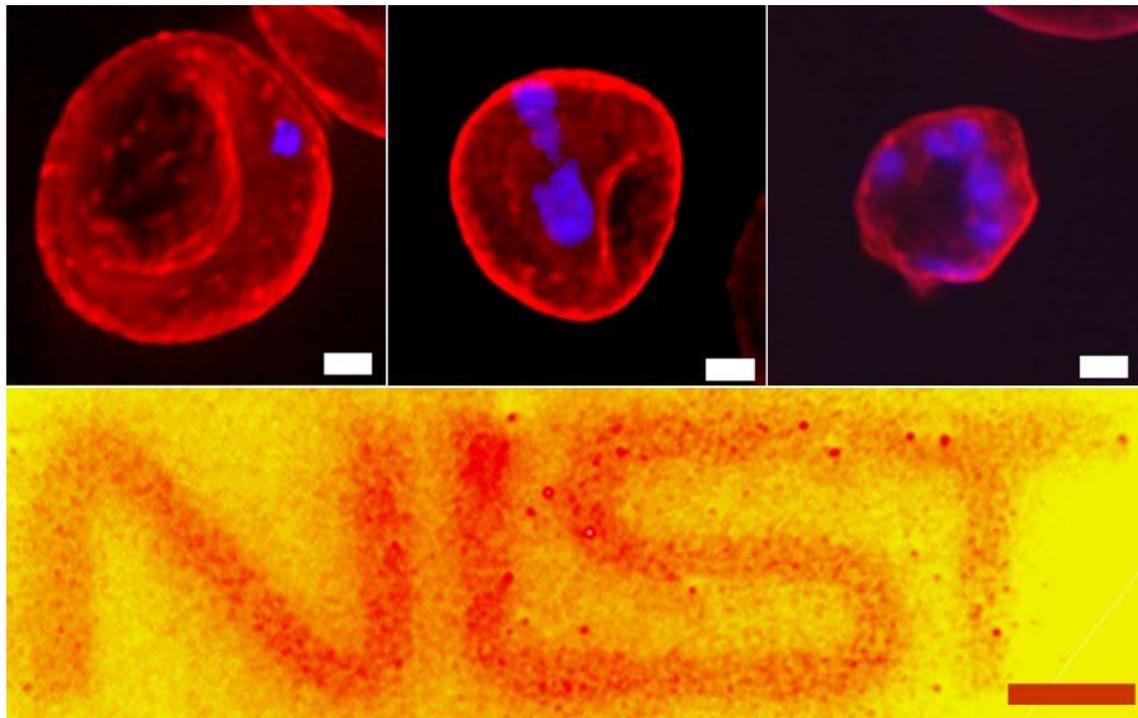
Quantum dots may one day power the world with clean, efficient energy

Solar cells can use quantum dots to convert sunlight into electricity more efficiently than conventional designs.

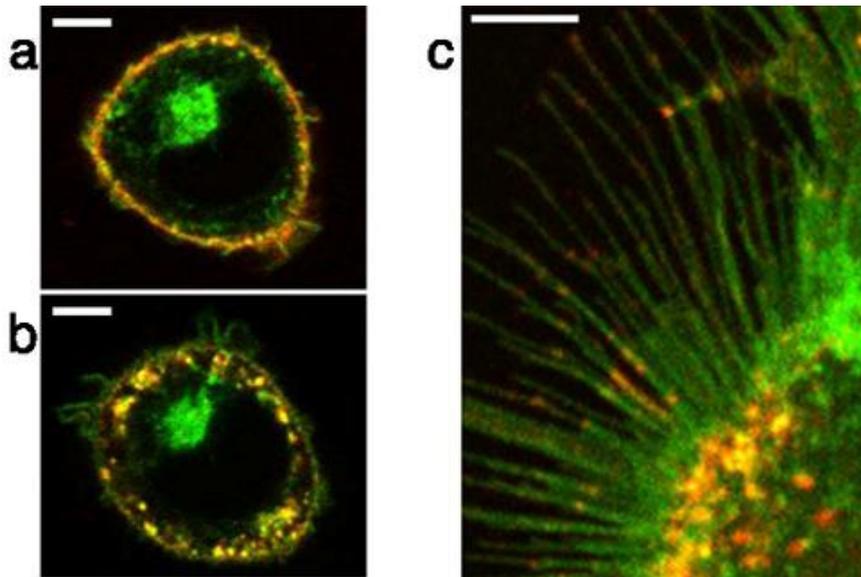
This technology is still in its early stages. Quantum dot solar cells are difficult to make and not yet cost effective.

Quantum Dots

Quantum dots may one day save your life. Medical imaging has begun to use colloidal (in liquid solution) quantum dots much like the ones you'll look at today. The photo below shows human red blood cells, in which specific membrane proteins are targeted and labeled with quantum dots. The number of purple features, which indicate the nuclei of malaria parasites, increases as malaria development progresses.



Quantum Dots

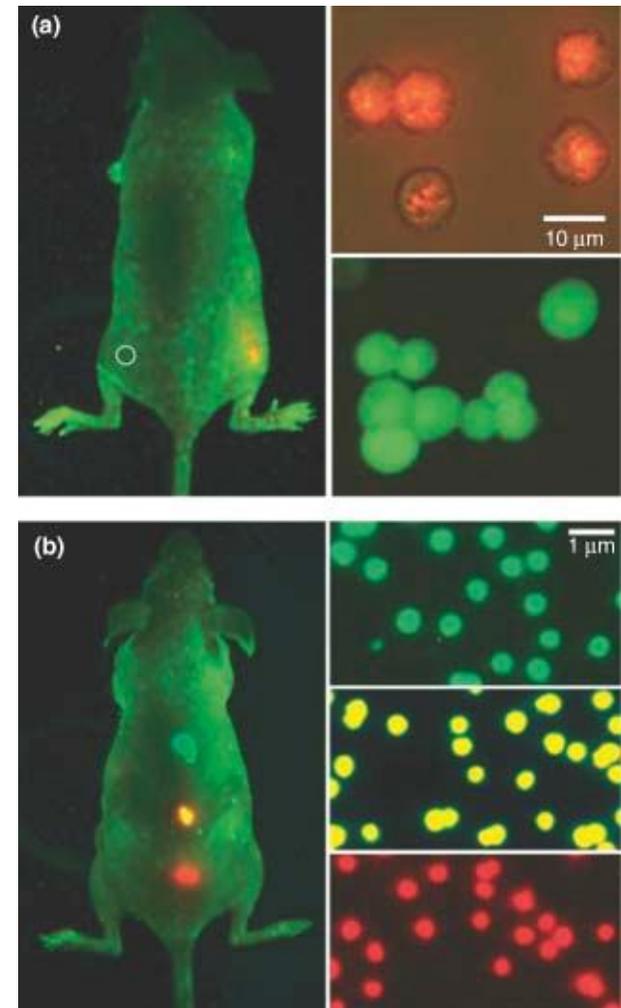
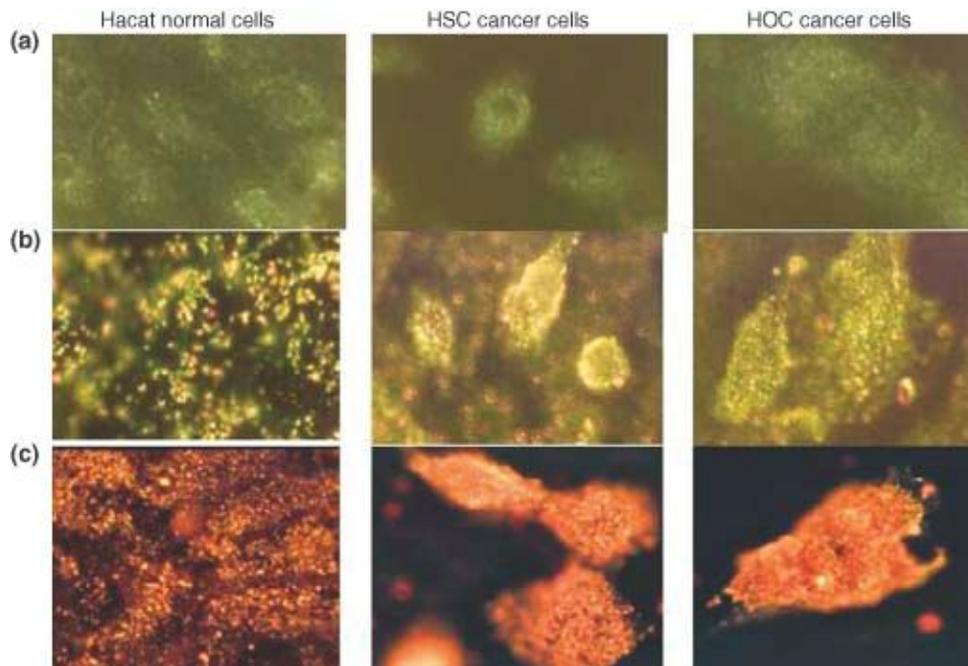


Quantum dots last longer in your system and are brighter than many organic dyes and fluorescent proteins previously used to illuminate the interiors of cells. They also have the advantage of monitoring changes in cellular processes (they last a long time) while most high-resolution techniques like only provide images of cellular processes frozen at one moment

Quantum dots (red dots above) can be designed to bind to specific cell receptors (green things). In this way researchers can monitor all kinds of processes in living cells

Quantum Dots

Quantum dots can target and illuminate cancer cells for earlier detection and a more precise diagnosis.



Left: Normal and cancer cells without quantum dot marking (top row) and with different quantum dot marking (middle and bottom)

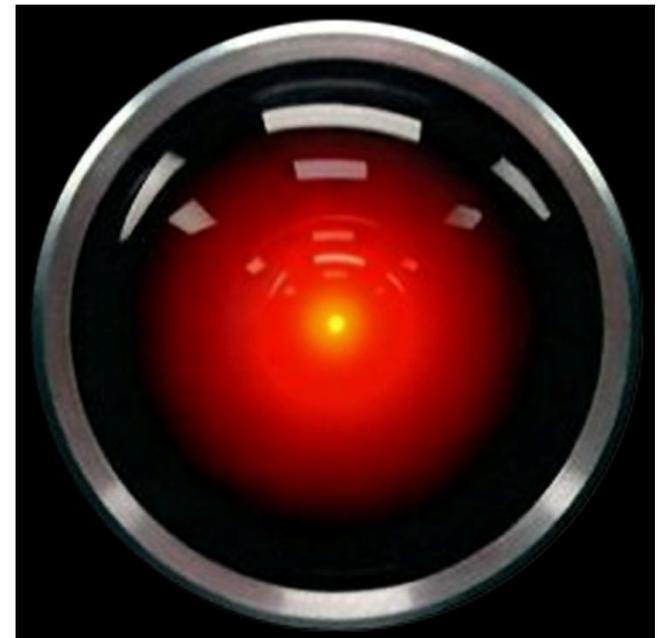
Top Right: cancer cells marked with standard methods (white circle) compared with quantum dot tagged cancer cells (bright orange)

Bottom Right: comparison of different types of quantum dots injected beneath the skin of a mouse

Quantum Dots

Quantum dots may be the future of computing. Lots of effort is currently being put into the field of spintronics (including us here) to progress toward quantum computers.

A quantum computer would use the spin of the electron instead of the charge like our current computers to process information. In this way it may use considerably less energy than a regular computer while being significantly faster. While the theoretical basis for these computers exists, any computer like we're used to is still far off.

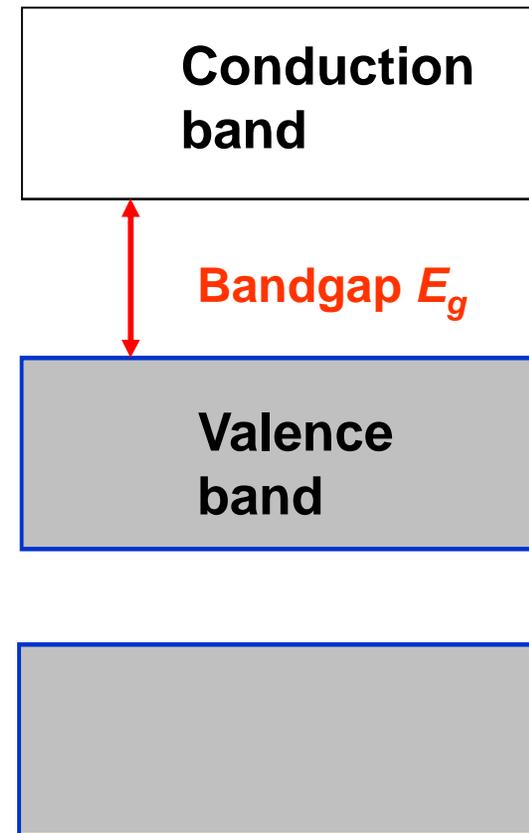
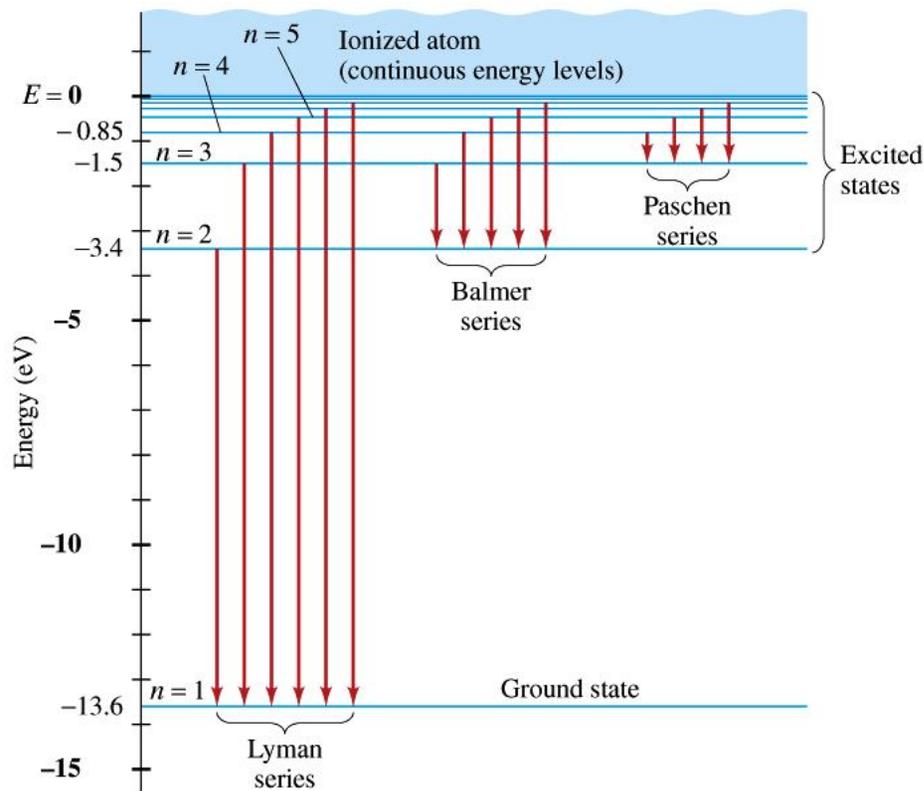


Luminescence spectra from InP quantum dots

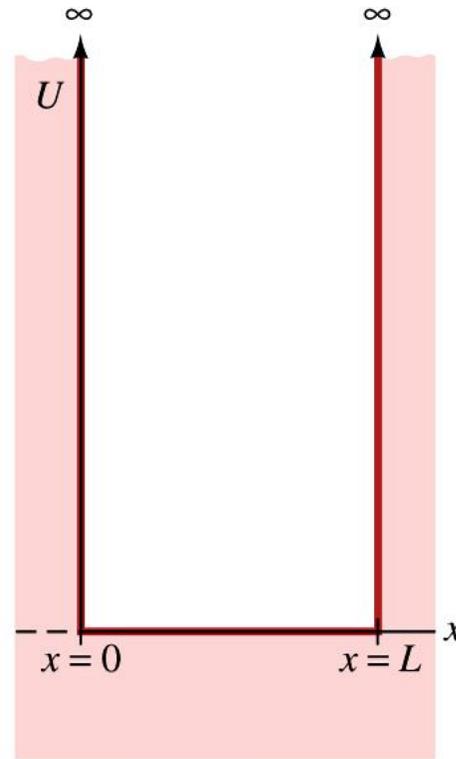
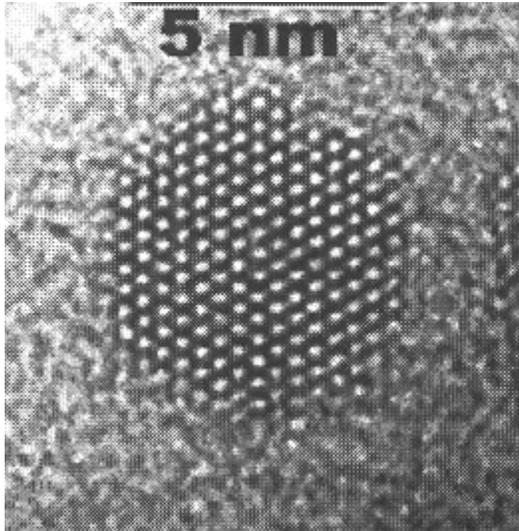
In this lab you will use a spectrometer to record the emission spectra from colloidal InP nanocrystals also known as “quantum dots.” You will record the spectra from four samples, each with a different nanocrystal radius. From these data you will determine the average nanocrystal radius as well as its range of values

Finally you will record the emission spectrum of the light source (light emitting diode LED) which you use to excite the QD spectra

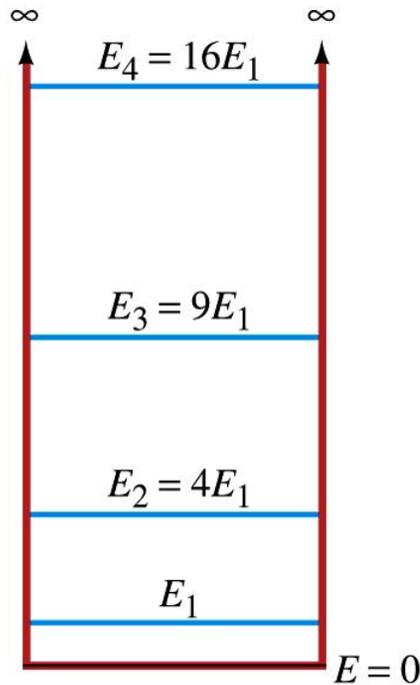
note: $\frac{1}{2}$ of you do PL in the morning and do the report and the other $\frac{1}{2}$ do absorption. We'll switch after lunch and each group does the other experiment



The energies of electrons in the hydrogen atom is shown to the left. The allowed energies are narrow. The situation is different in solids such as InP as shown in the picture to the right. The allowed energy states are now broad and for this reason they are called “**bands**”. The highest energy filled state is called the “**valence band**” and the next empty state is known as the “**conduction band**”. The distance between the bottom of the conduction band and the top of the valence band is called the **bandgap** of the solid (symbol: E_g).



The figure to the left is an electron microscope picture of an InP nanocrystal known also as quantum dots (QD). Each point represents an atom. The electrons in each QD are confined to move inside the nanocrystal. The potential which confines them is shown in the figure to the right. It is known as an “infinite quantum well”



The confinement of the electrons results in the appearance of the energy states shown in the figure. The energy of the lowest state is given by:

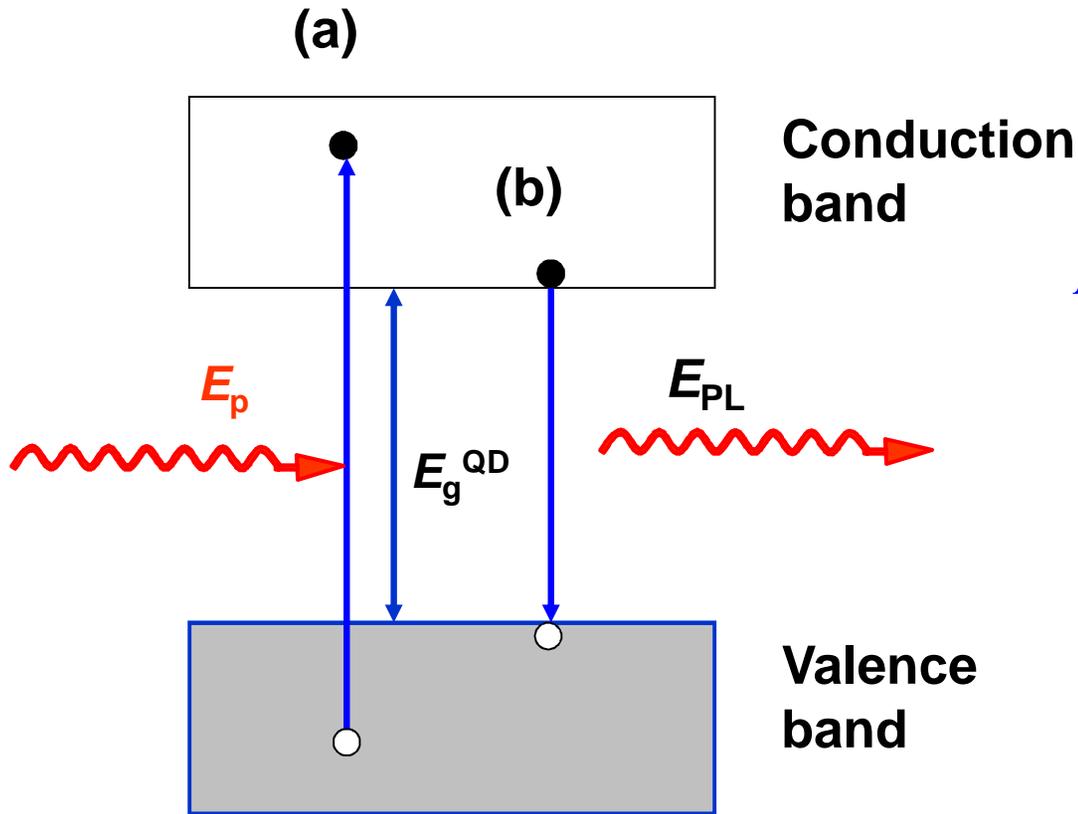
$$E_1 = \frac{\pi^2 \hbar^2}{2mL^2}$$

The energy of the other states is:

$$E_n = \frac{\pi^2 \hbar^2}{2mL^2} n^2 = E_1 n^2$$

Confinement of the nanocrystal electrons results in an **increase** of the bandgap according to the equation:

$$E_g^{OD} = E_g^{bulk} + \frac{\hbar^2 \pi^2}{2R^2} \left(\frac{1}{m_e} + \frac{1}{m_h} \right)$$

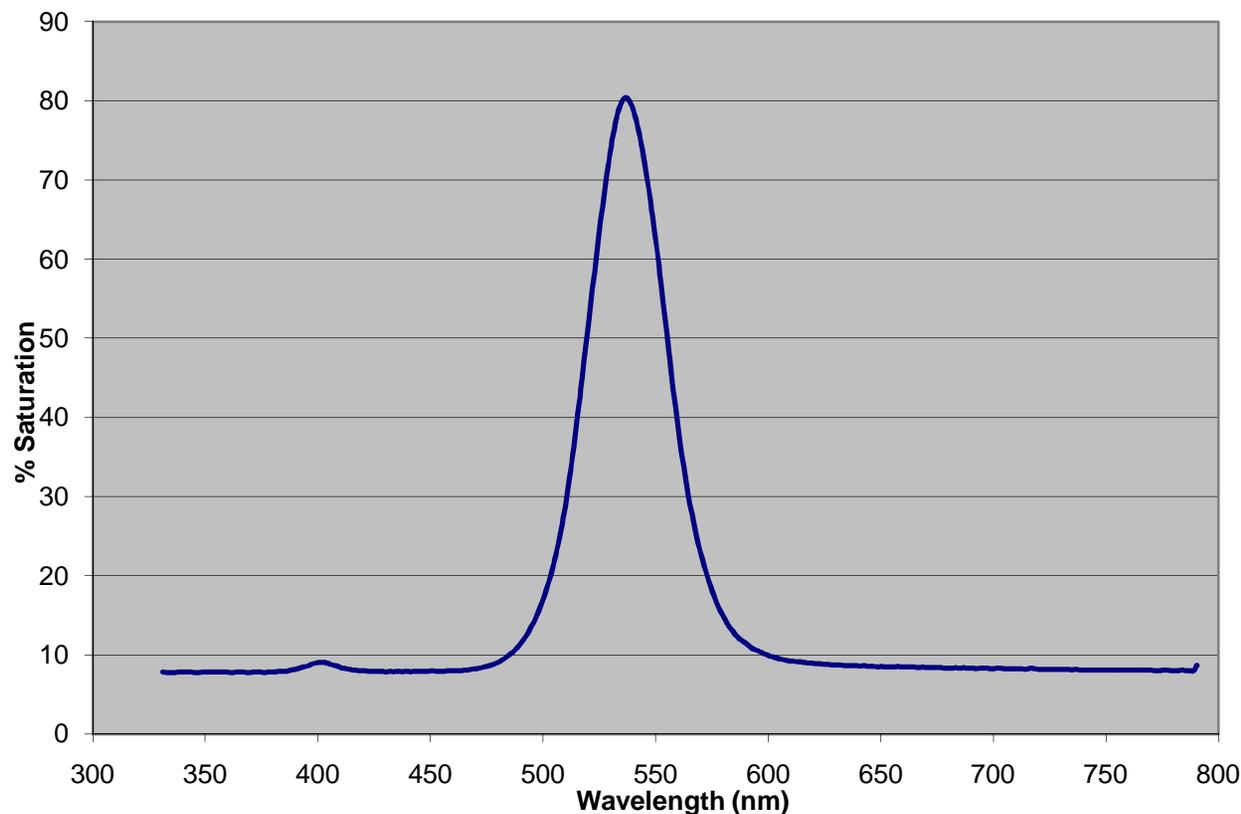


$$E_g^{QD} = E_g^{bulk} + \frac{\hbar^2 \pi^2}{2R^2} \left(\frac{1}{m_e} + \frac{1}{m_h} \right)$$

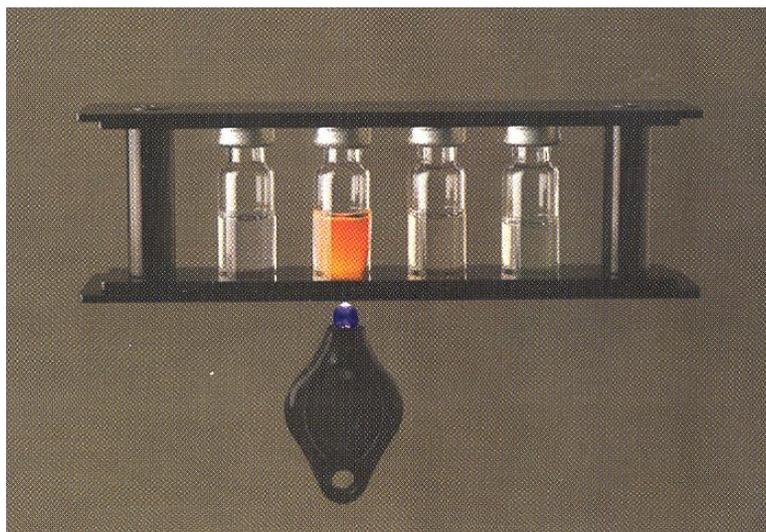
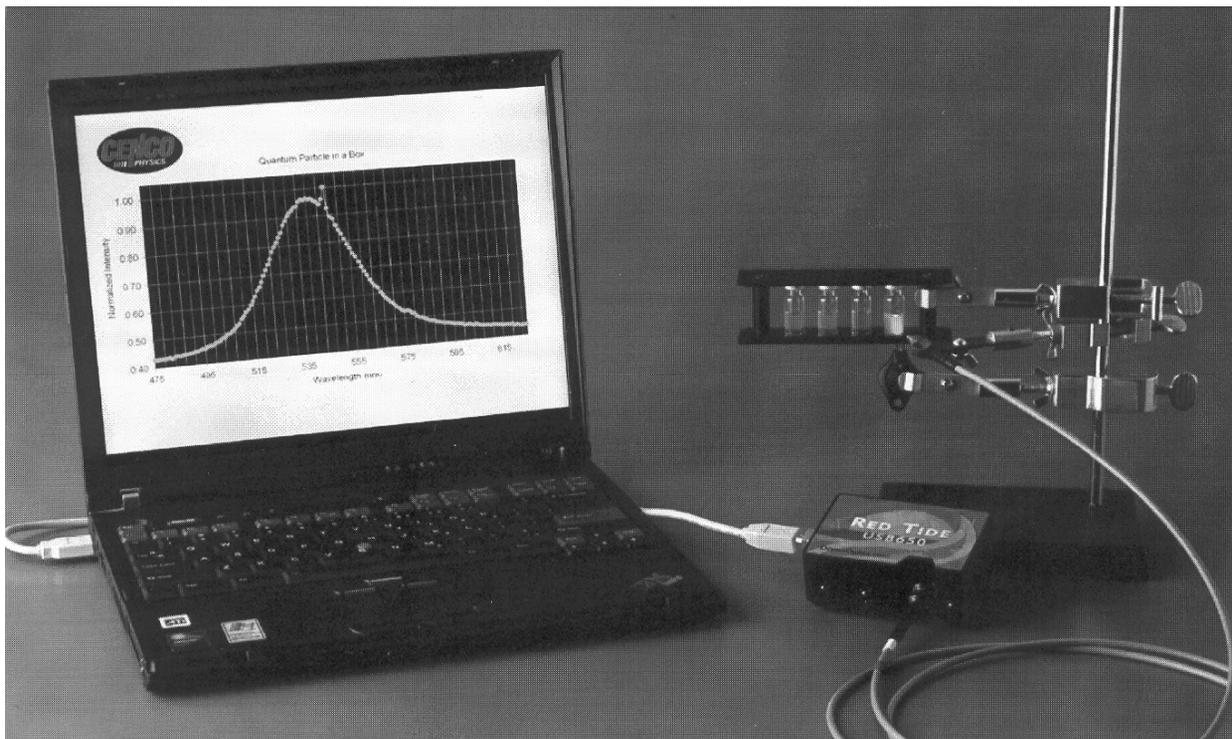
Notice that the smaller the radius of a quantum dot, the larger the bandgap. This means you can control the color of the light emitted by the dots by changing their size!

The incident photon E_p excites an electron from the filled valence band and promotes it to the next empty band known as the conduction band leaving a hole behind. The electron and the hole relax to the bottom of the conduction and top of the valence band, respectively. Then they recombine emitting a photon whose energy E_{PL} is equal to the bandgap of the quantum dot

Green PL

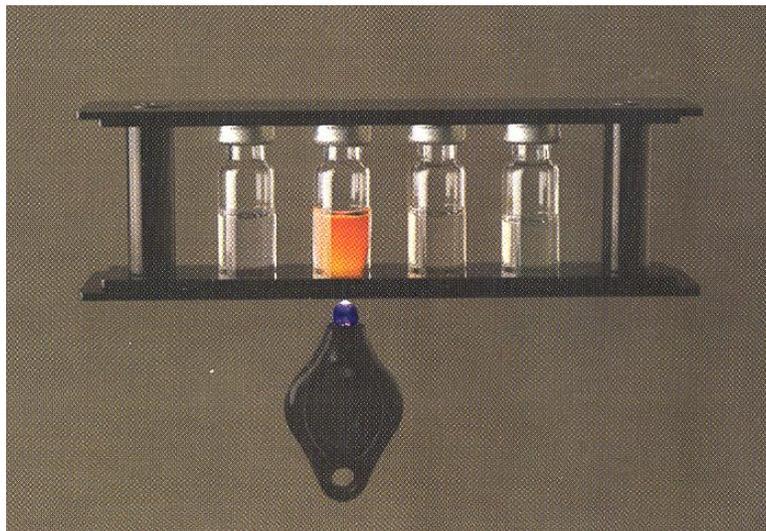


The light that we see emitted by a quantum dot tells us something about the size of the dot itself. However, a liquid solution of dots that might look like they all emit the same color light actually emit a range of colors. This tells us that not all the dots are exactly the same size. In this experiment you will use a PL spectrum like the one above to calculate what this range of sizes is as well as the average size.



Upper picture: Experimental setup. An optical fiber cable collects the light emitted from each sample

Bottom picture: The four samples used in this experiment. The light source is a UV diode and can be seen under the second sample from the left.



Sections V1-V5

V1: Place the LED under the leftmost sample and illuminate it from the bottom. Place the tip of the optical fiber cable in contact with the illuminated sample. Record the emission spectrum **using the instructions in the lab handout.**

V2-V4: Repeat the above step for the second, third, and fourth sample.

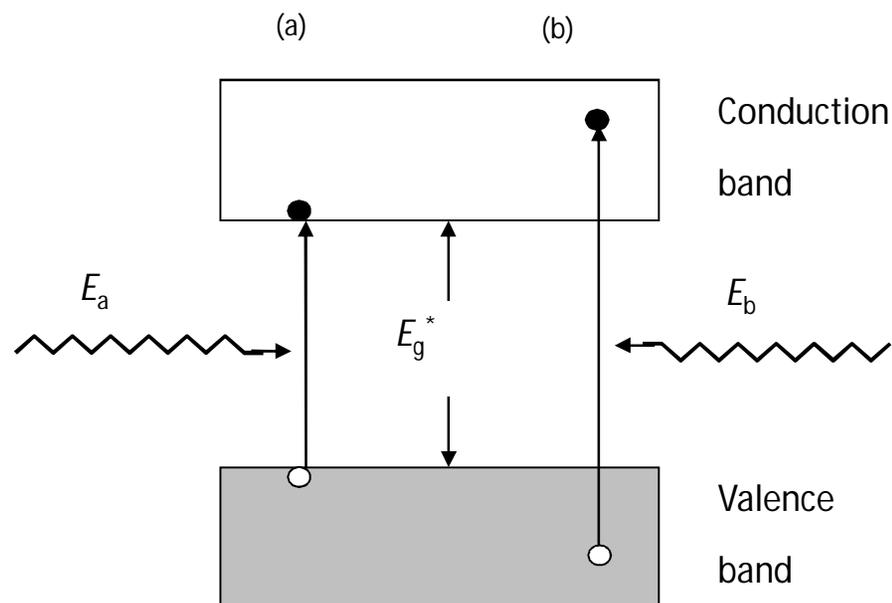
V5: Place the tip of the optical fiber cable approximately 1 cm from the LED. Record the LED emission spectrum. **The LED can be dangerous. Do not look directly down into the LED.**

You will export all the files into excel using the instructions in the lab handout

Absorption spectra of CdSe quantum dots

For this part of the lab you will use a spectrometer to record the absorption spectra from CdSe nanocrystals also known as “quantum dots.” You will record the spectra from three glass filters, each with a different nanocrystal radius. From these data you will determine the nanocrystal bandgaps and corresponding radii.

These filters aren’t just painted or colored glass, but actually quantum dots inside of the glass itself.



The underlying physics is identical to the InP quantum dots.

The necessary condition for optical absorption to occur is that the energy of the incident photon must exceed the bandgap of the semiconductor: Such a process is shown on the right (labeled process *b*). The incident photon of energy E_b is annihilated and its energy is transferred to a valence band electron which is promoted to the empty conduction band (indicated by a filled circle). The valence band electron leaves a “hole” i.e. an unoccupied state in the valence band (indicated by an open circle)

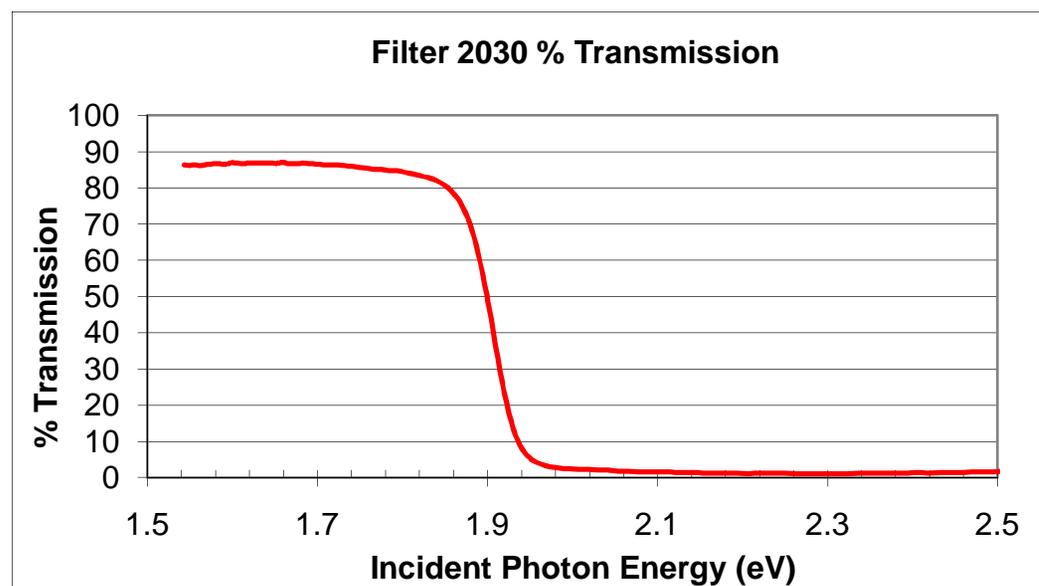
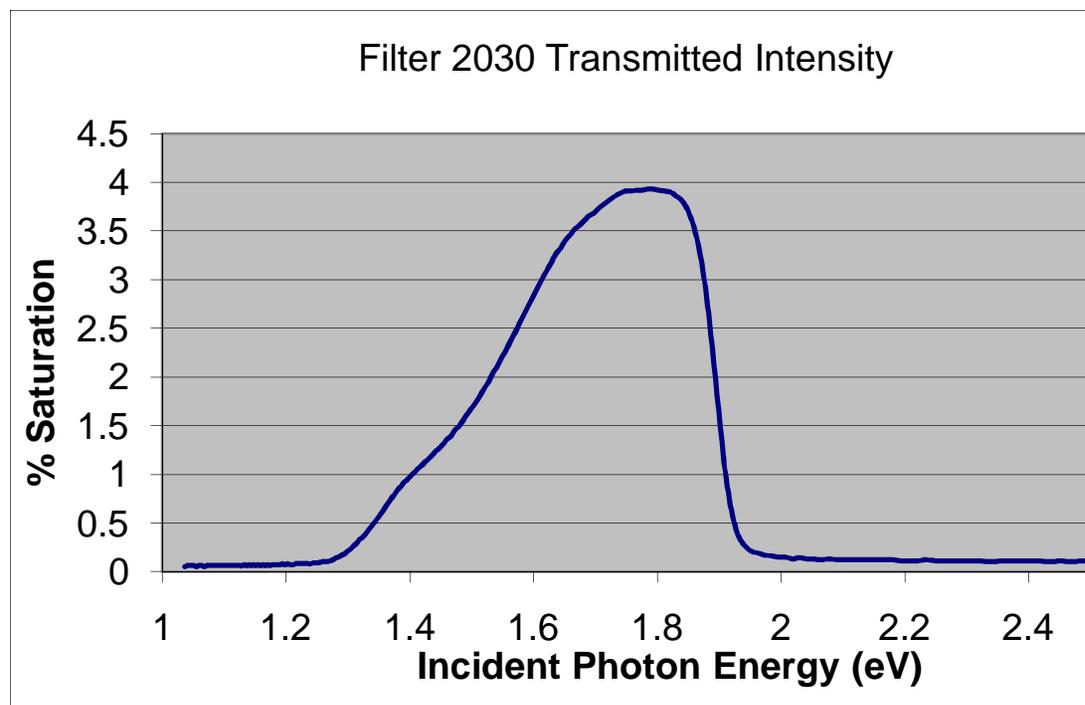
In process *a* the limiting case ($E_{\text{photon}} = E_g^*$) of the smallest energy photon that can be absorbed is shown. For photon energies less than the bandgap the incident photon is not absorbed but is transmitted through the semiconductor. This is what gives the filters their color.

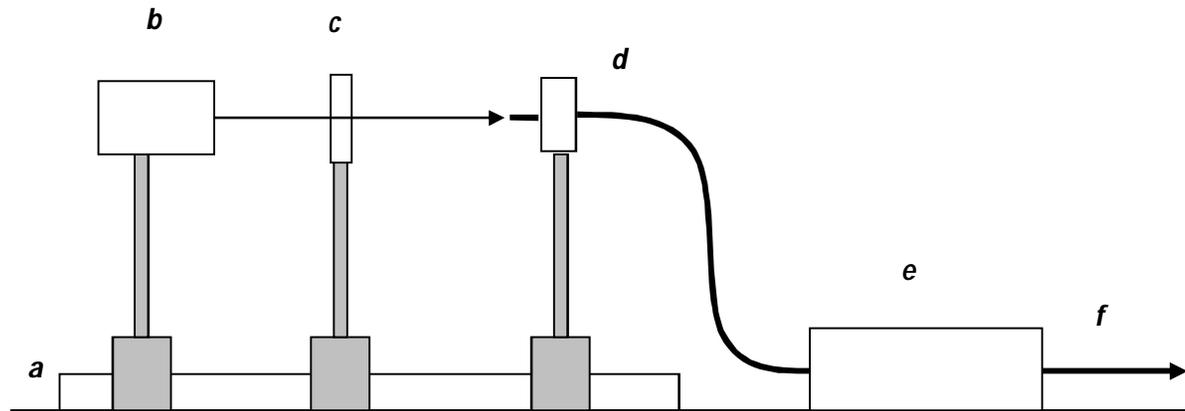
Once again the light we see passing through the filter tells us something about the bandgap of the quantum dots and thus their size.

You'll use the spectrometer to capture a transmission spectrum like the upper graph on the right.

The software does the work for you and converts this spectrum to a % transmission spectrum like the one on the lower right using the lamp spectrum (incident light) and the equation:

$$T = \frac{I_{transmitted}}{I_{incident}}$$





The experimental setup. An incandescent lamp is mounted at *b*. The filter is placed at *c* between the lamp and the optical fiber at *d*.

Sections V1-V3

V1a: Record the dark count with all lights off and no filter **using the instructions in the lab handout.**

V1b: Record the lamp spectrum with no filter in the holder **using the instructions in the lab handout.**

V1c: Record the light transmitted by the first filter **using the instructions in the lab handout.**

V1d: Subtract the dark count **using the instructions in the lab handout.**

V1e: Calculate the transmission spectrum **using the instructions in the lab handout.**

V1f: Export your data so you can plot it in excel **using the instructions in the lab handout.**

V2-V3: Repeat these steps for the other two filters

Important Quantities

For InP

$$E_g^{bulk} = 2.15 \times 10^{-19} \text{ J}$$

$$m_e = 7.29 \times 10^{-32} \text{ kg}$$

$$m_h = 5.47 \times 10^{-31} \text{ kg}$$

For CdSe

$$E_g^{bulk} = 2.78 \times 10^{-19} \text{ J}$$

$$m_e = 1.18 \times 10^{-31} \text{ kg}$$

$$m_h = 2.39 \times 10^{-30} \text{ kg}$$

$$R = \sqrt{\frac{\hbar^2 \pi^2 \left(\frac{1}{m_e} + \frac{1}{m_h} \right)}{2 \left(E_g^{QD} - E_g^{bulk} \right)}}$$