Light Emitting Diodes: Devices for Teaching Some Applications of Quantum Physics

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Kansas State University Physics Education Research

Manhattan,
Kansas

http://asiapacific.anu.edu.au/mapsonline

Today

- Start with a video of a short experiment
- Consider how to use this experiment to teach some quantum physics
- Focus on students building scientific models
  - Empirical model
  - Wave function model

Experiment with an array of LEDs

Arbor Scientific

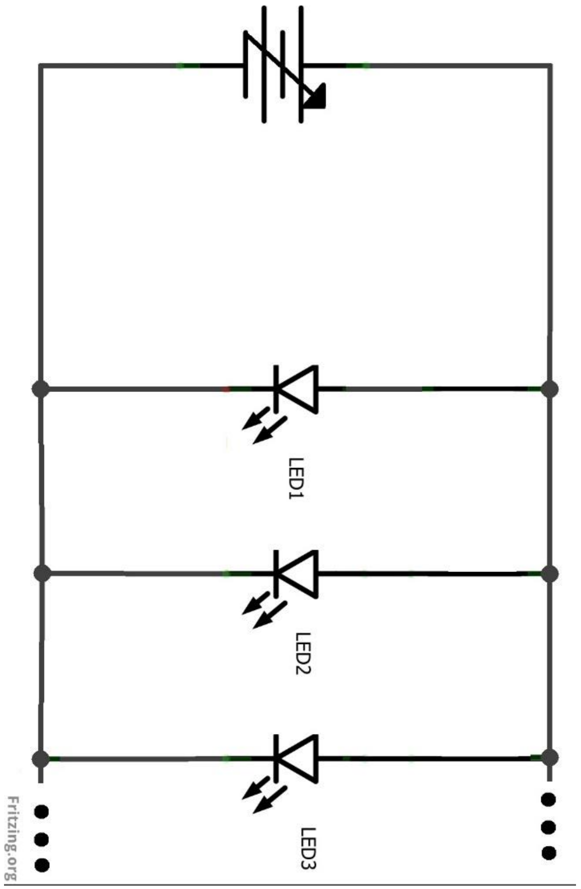
Udine (Italy) Physics Education Research Group

https://youtu.be/Qt2KIFnrdkw

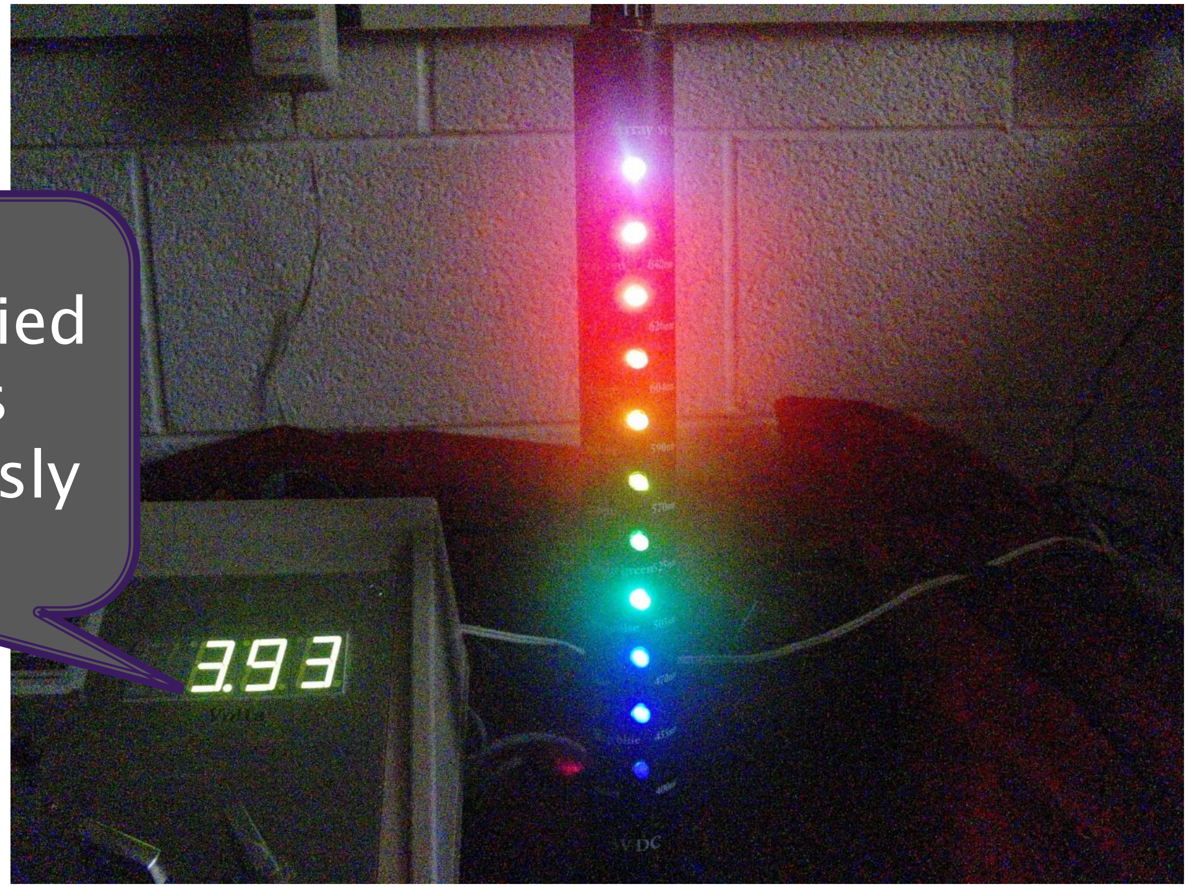
Labels on the device

11LEDs

- White
- Deep Red 640 nm
- Red 626 nm
- Orange 604 nm
- …
- Blue 470 nm
- Deep Blue 455 nm
- Violet 400 nm



Vary voltage on all of the LEDs



Voltage applied to all LEDs simultaneously

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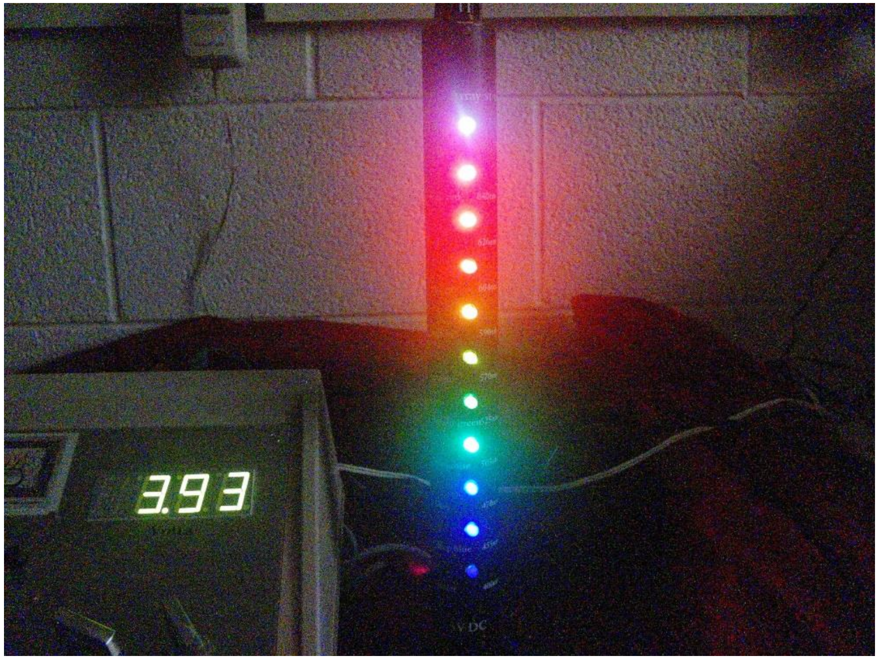
Watch a video of the experiment, then we will discuss your observations



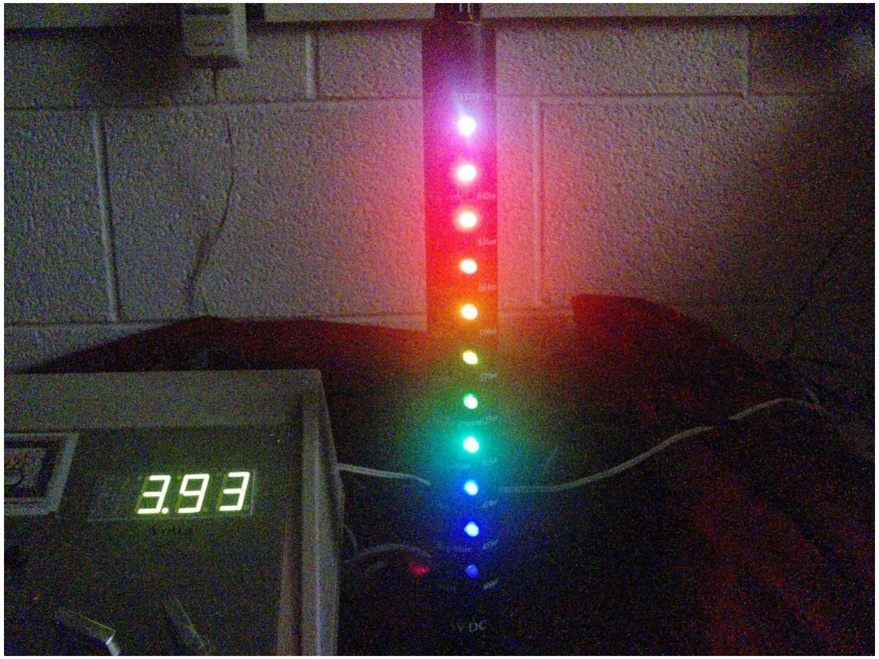
https://youtu.be/uy-xTadGobY

What did you observe?

Talk to your neighbor first, then I will collect observations.

What did you observe?

Watch again with a little scaffolding



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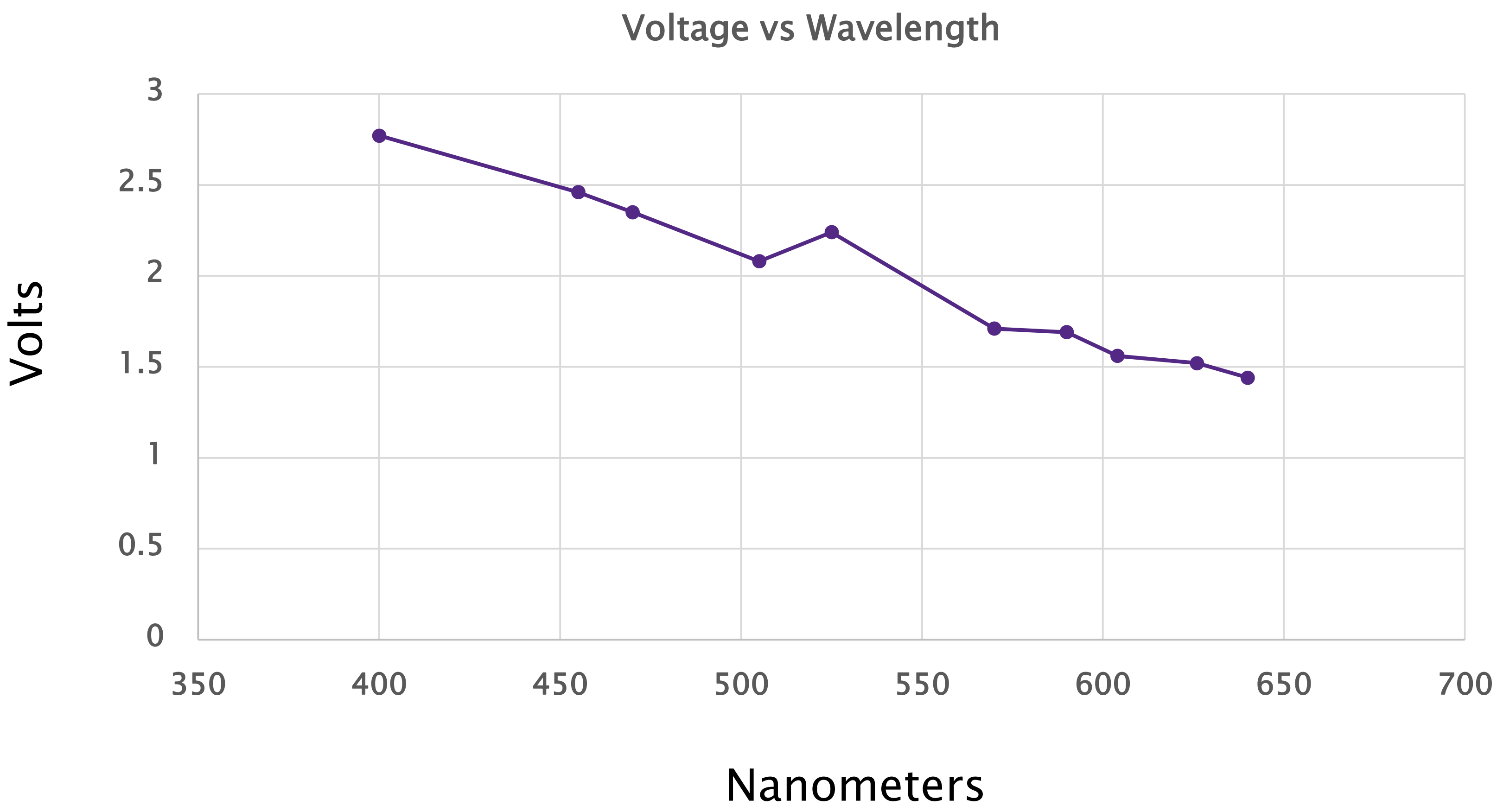
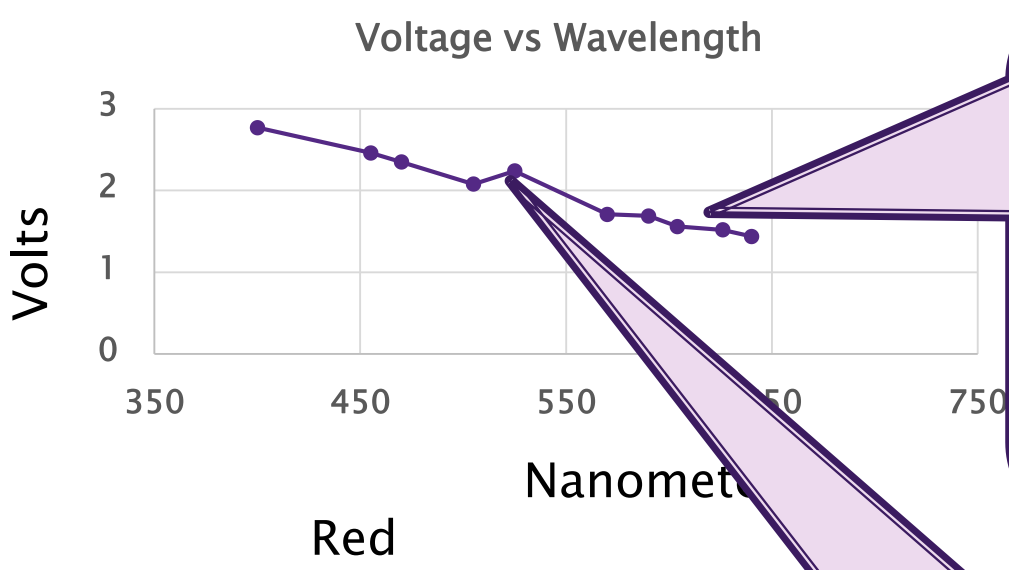

Voltage vs Wavelength
3
2.5
2
1.5
1
0.5
0
350
400
450
500
550
600
650
700
Volts
Nanometers



Why does the graph show almost straight line behavior?

Why does this LED seem to deviate from the straight line?

Two approaches to having students learn about the LED as an application of quantum physics

Phenomenology
- Spectra of gases
- Energy levels
- Multiple atoms
- Multiple energy levels
- Energy bands & gaps
- Spectra of LEDs

Wave functions
- Particle in a well
- Energy levels
- Spectra of gases
- Wave functions in multiple wells
- Energy bands & gaps
- Spectra of LEDs

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Knowledge needed before starting

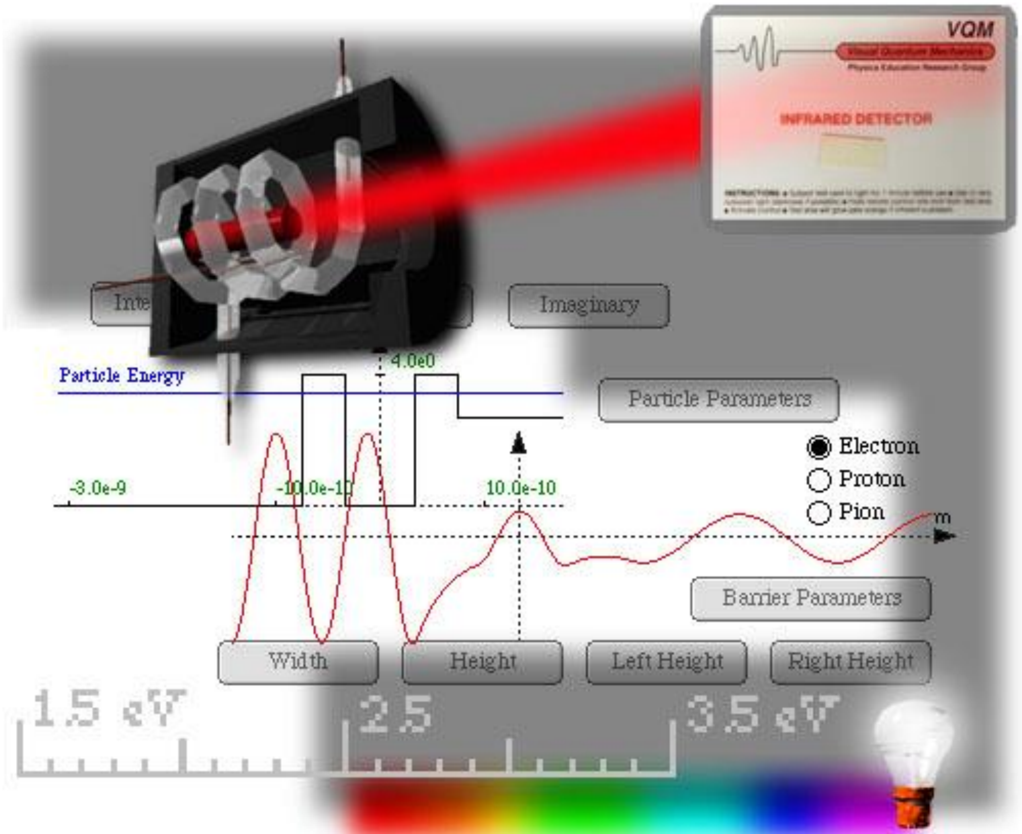
Phenomenology

- Conservation of Energy
- Light energy comes in packets (photons)
- Light energy is related to color

Wave function

- Wave functions describe electron behavior
- Standing waves
- Conservation of Energy
- Light energy comes in packets (photons)
- Light energy is related to color

Phenomenological Approach
Visual Quantum Mechanics



http://www.phys.ksu.edu/ksuper/research/vqm

Visual Quantum Mechanics
Instructional materials for different types of students

- Secondary school students
- Science & Non-science university students
- Present & Future Teachers
- Upper-level Physics Students
- Web surfing public

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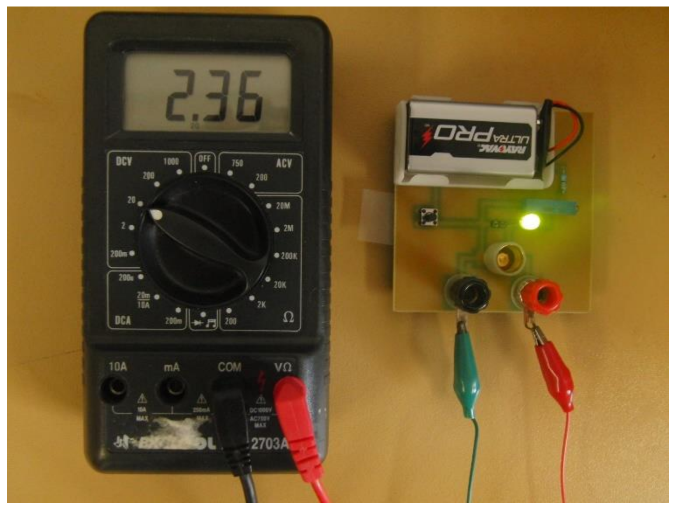
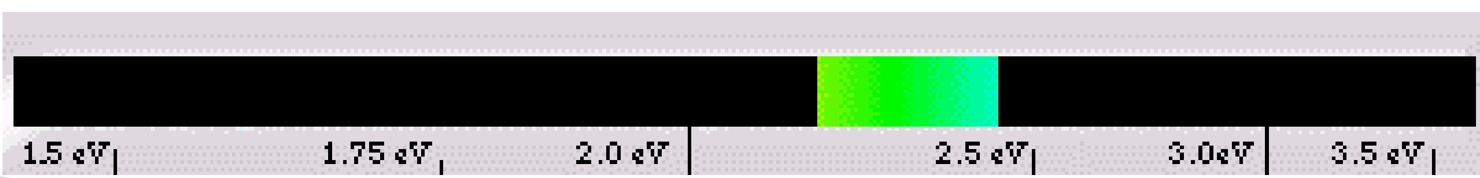
Learning unit: Solids & Light

Students start with an experiment similar to the one that we just did.

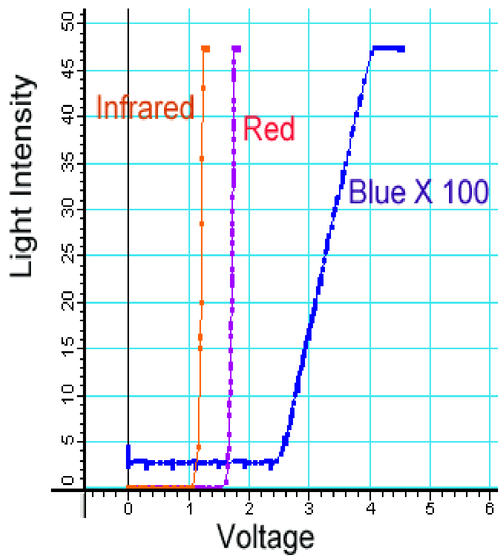
Students explore properties of the LED by observing

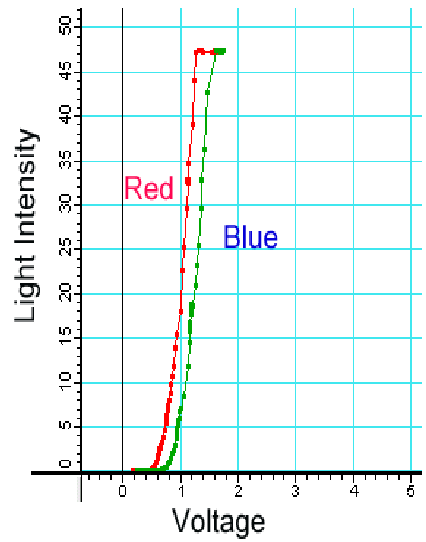
- Threshold energy for light emission
- Spectra of emitted light.





Voltage vs. Light Intensity





Light Emitting Diode

Data collected with Pasco interface

Incandescent lamp

Observations of *LED*

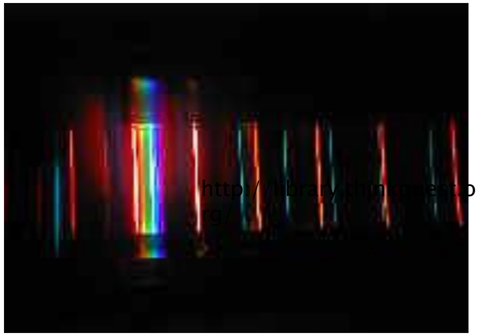
- LED: light only above a threshold energy.
- LED: threshold energy depends on color
- Colors of light from clear LEDs
  - Not true of other light sources
- Direction of current in LED is important

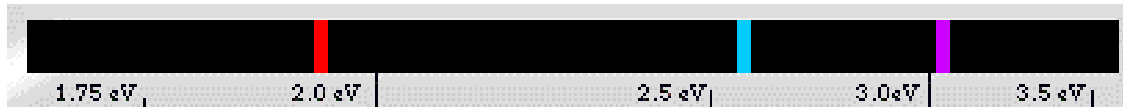
So, we must investigate LEDs more carefully

Starting to construct a model

- An LED is a solid state device.
- Solids are more complex to understand than gases.
- So first explore light from Gas Lamps.

Gas lamp spectra



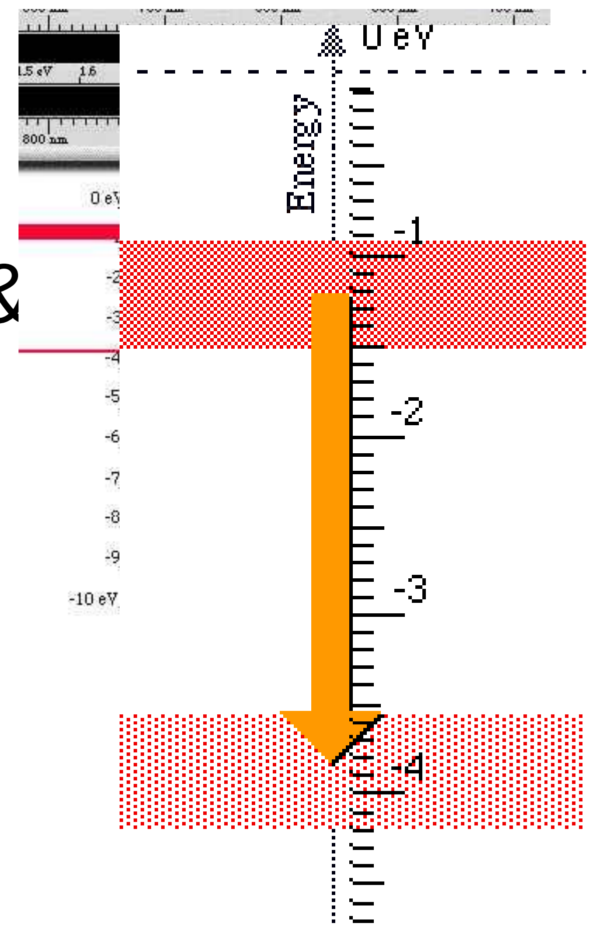


- Observe that gas spectra have discrete energies of light.

- Use *Spectroscopy Lab Suite* program to construct energy level diagram.

Continuing to build a model for LED light emission

- LEDs show bands of color.
- Gases have lines of color & discrete energy levels, so
- LEDs must have closely spaced energy levels



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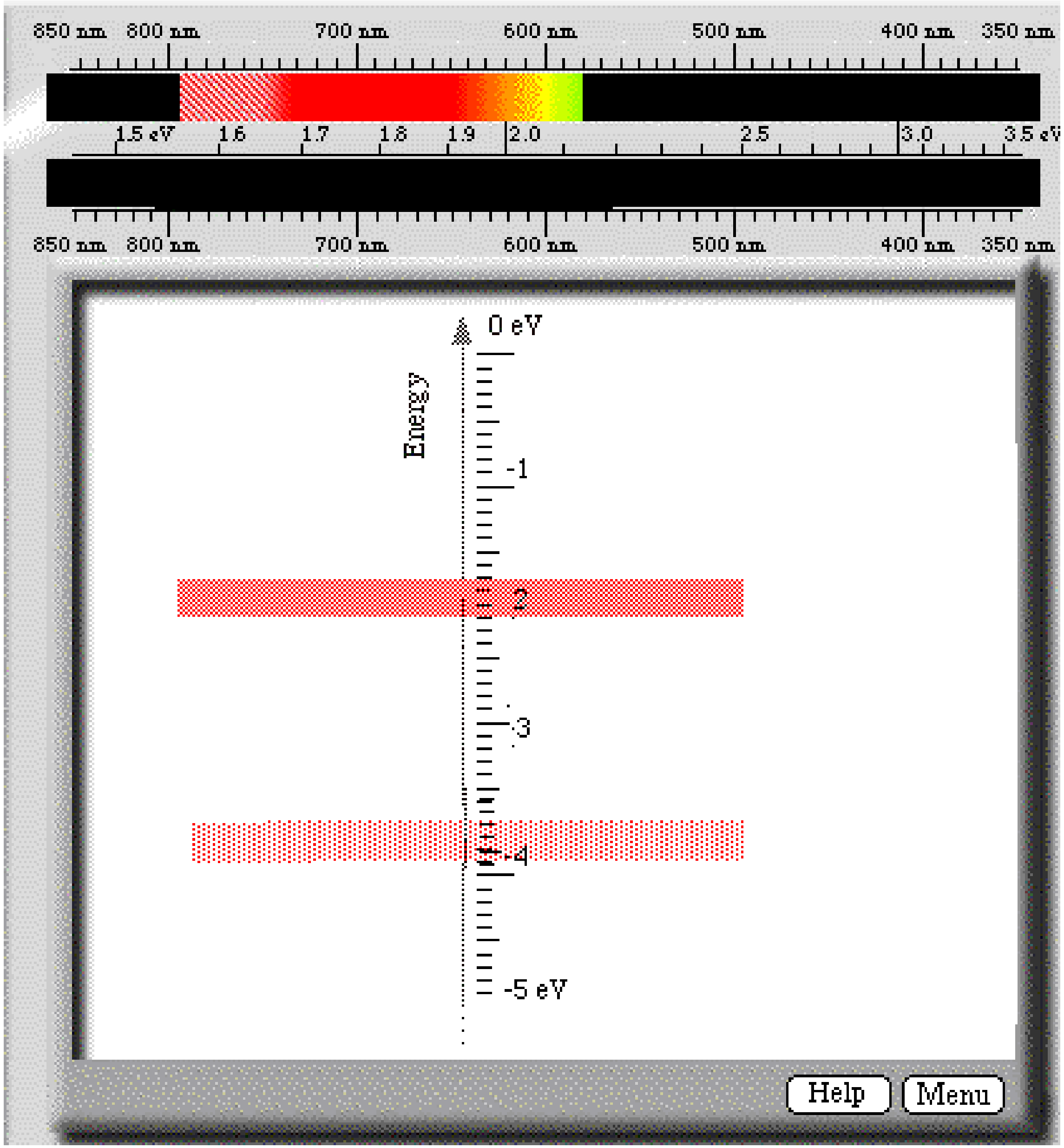
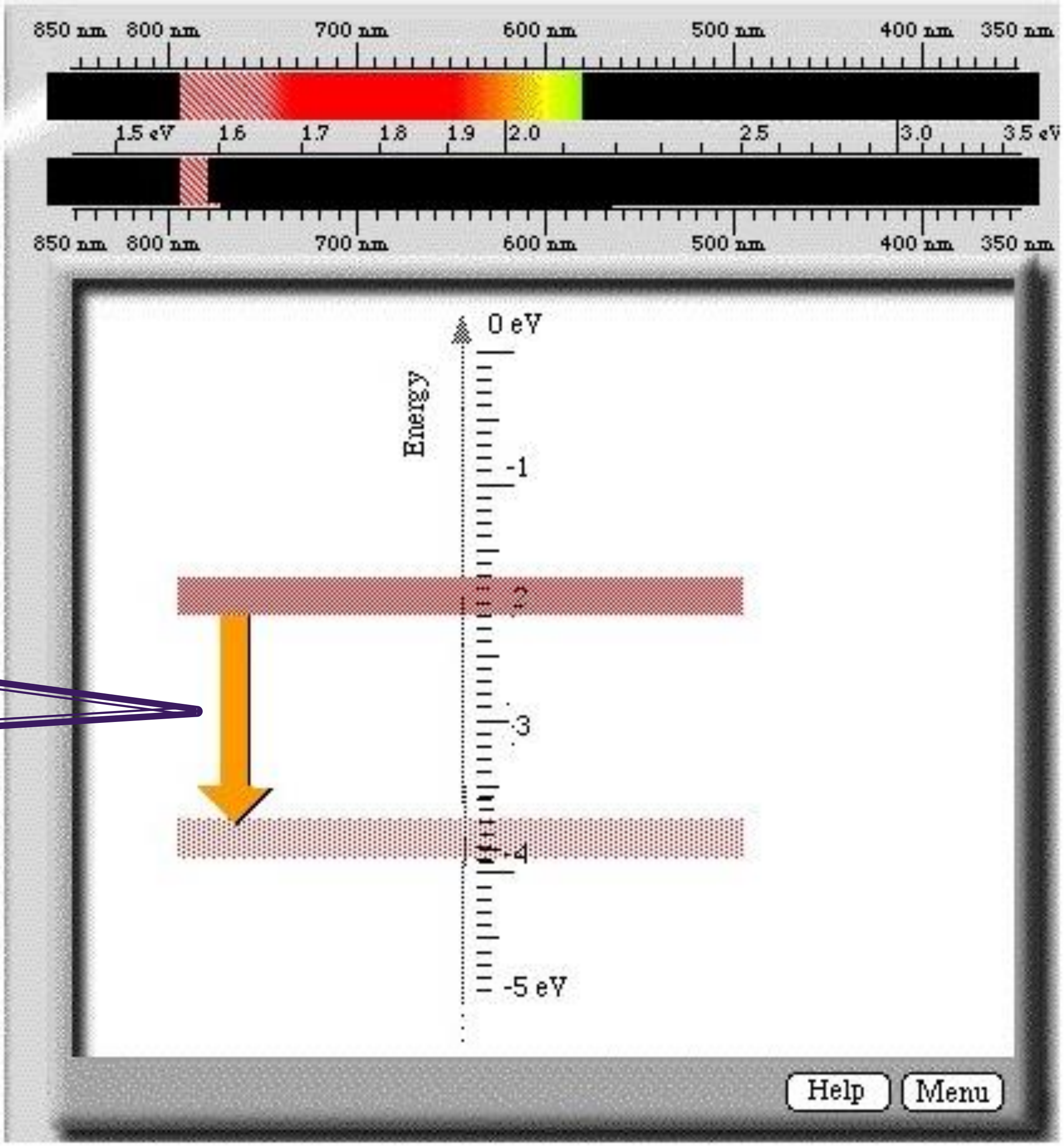
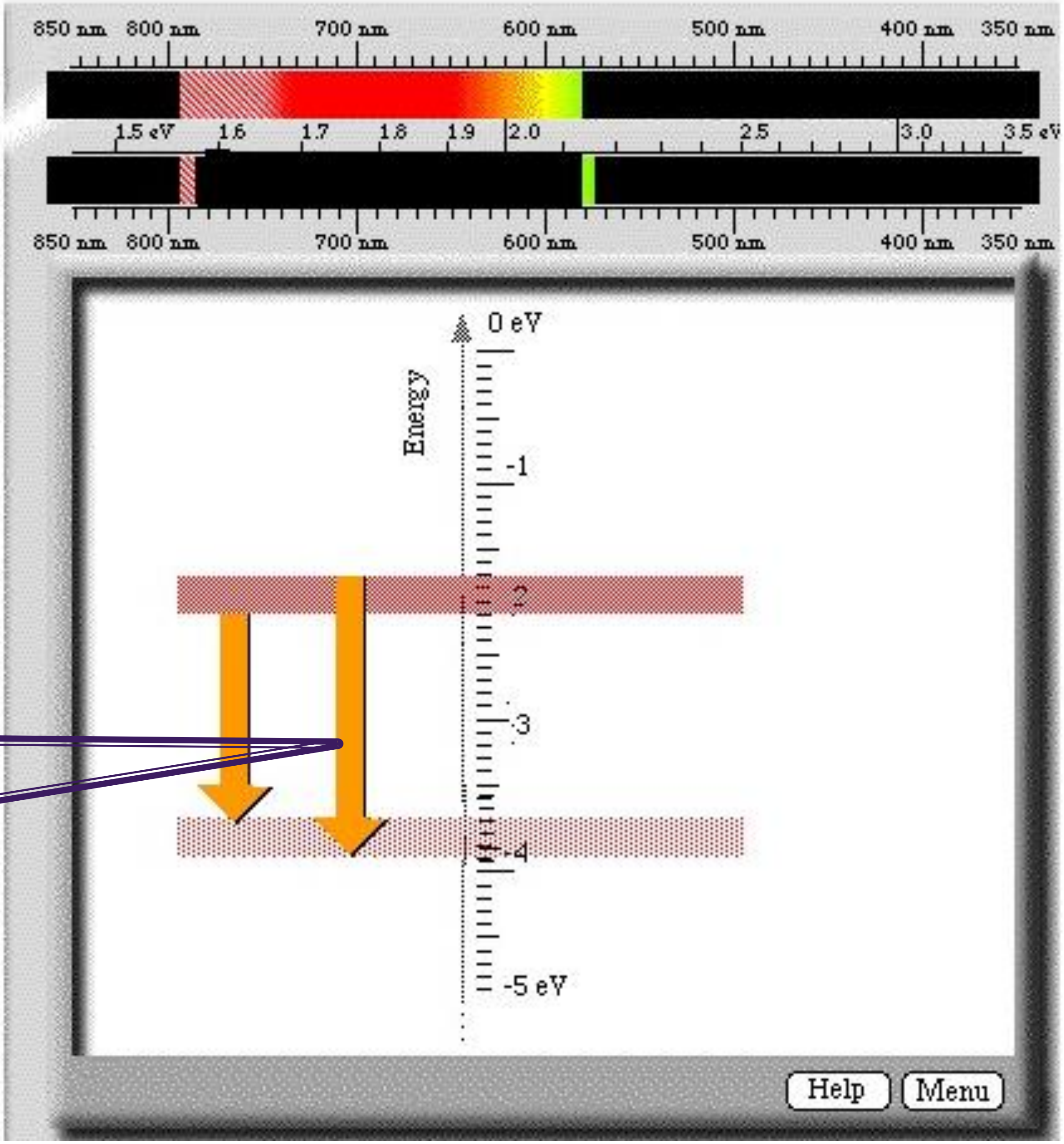

850 nm
800 nm
700 nm
600 nm
500 nm
400 nm
350 nm
1.5 eV
1.6
1.7
1.8
1.9
2.0
2.5
3.0
3.5 eV
0 eV
Energy
-1
-2
-3
-4
-5 eV
Help
Menu

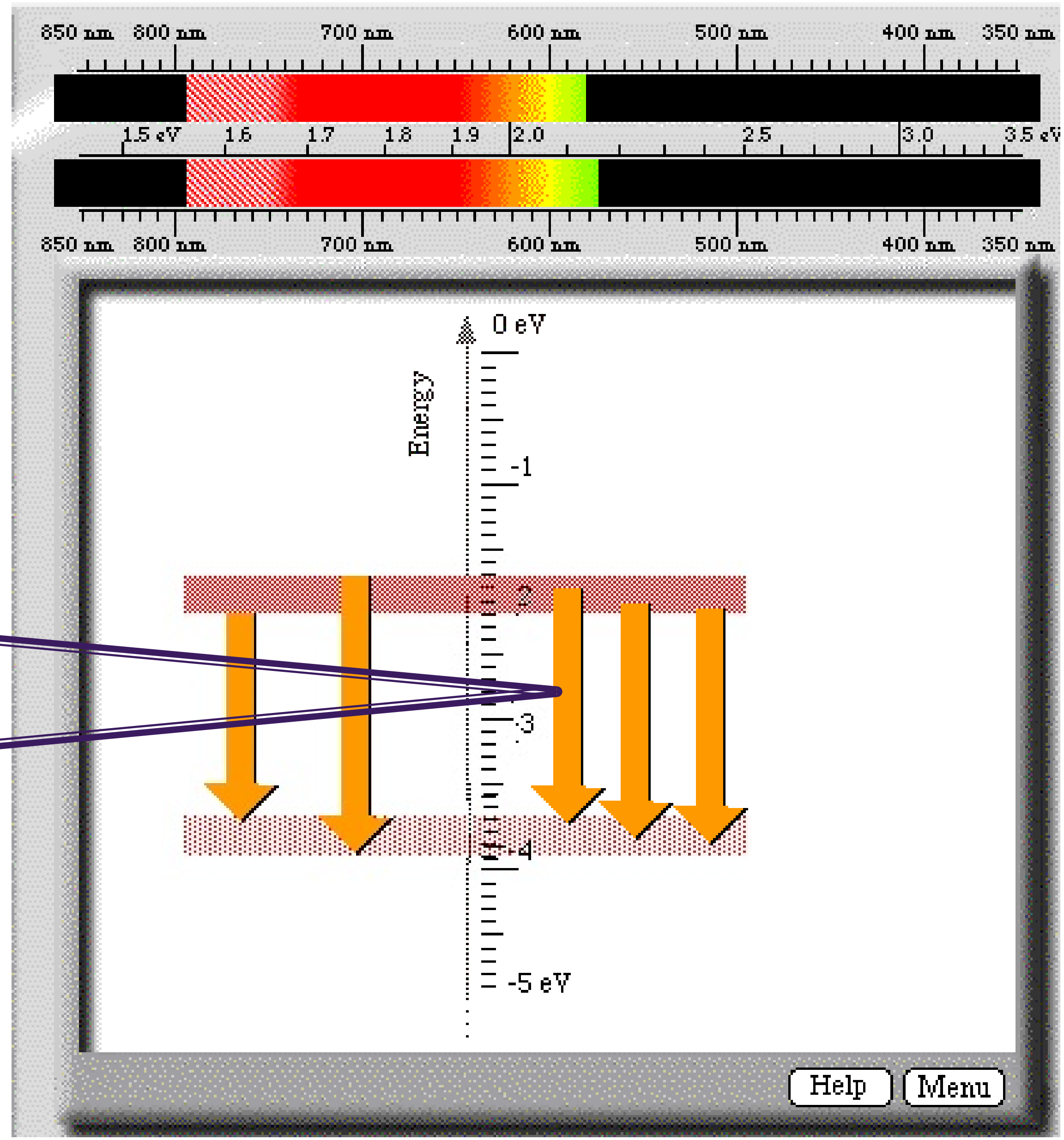
Lowest energy of light



Maximum energy of light

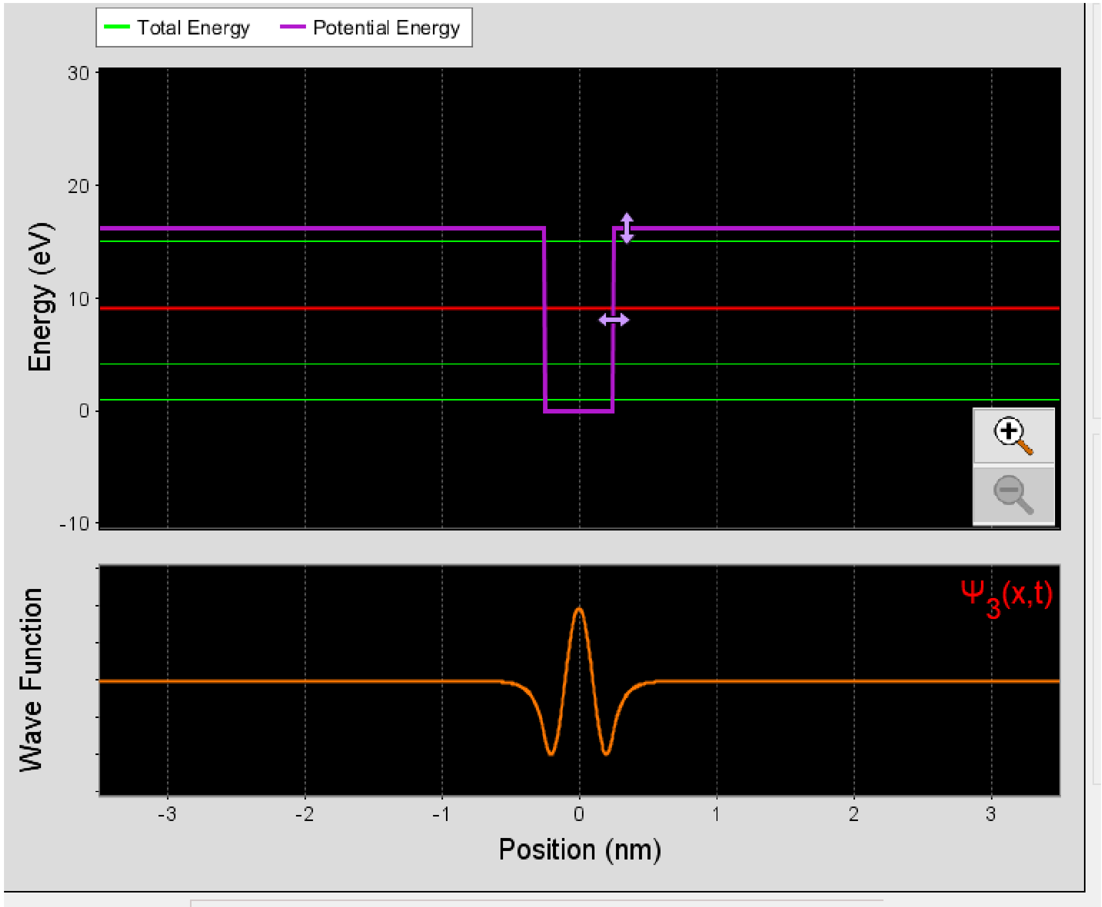


Within bands transitions, many other energies of light



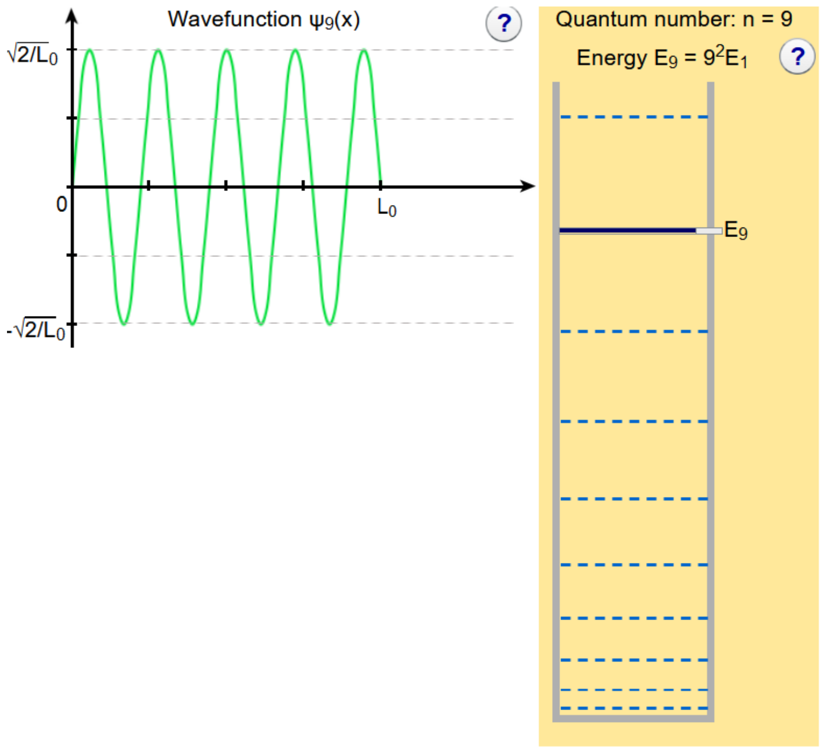
Wave Function Approach

Start with wave function & energy levels for a single square well



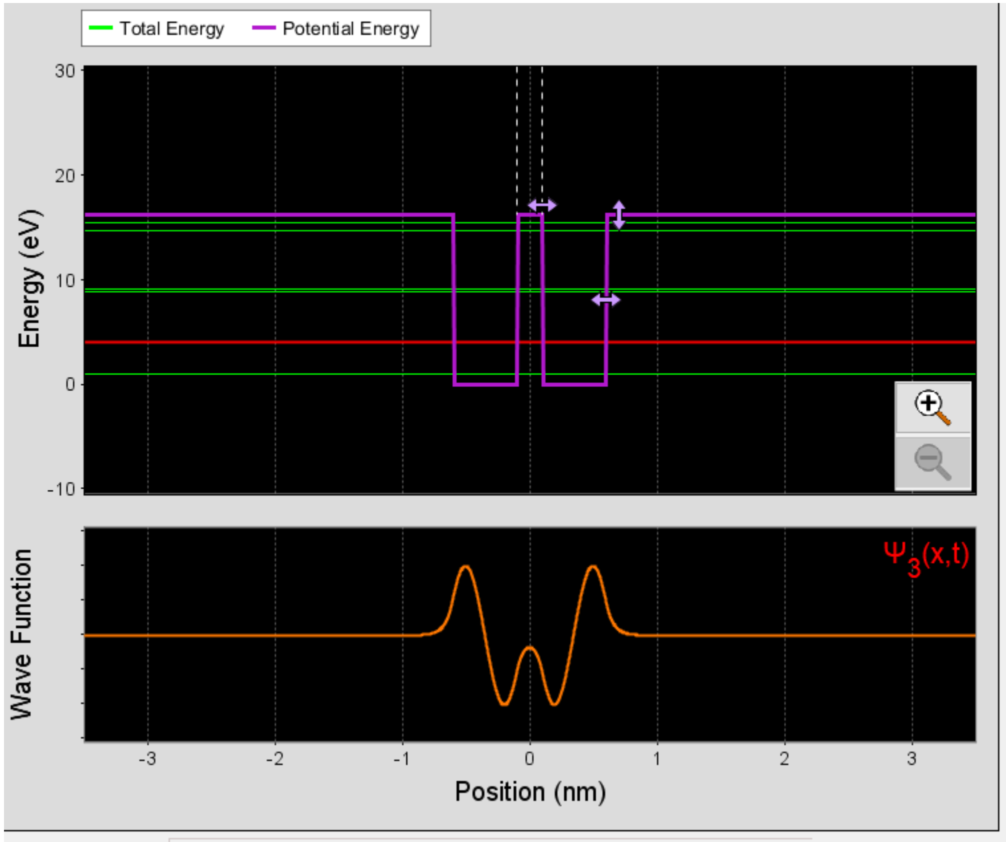
https://phet.colorado.edu/

Start with wave function & energy levels for a single square well

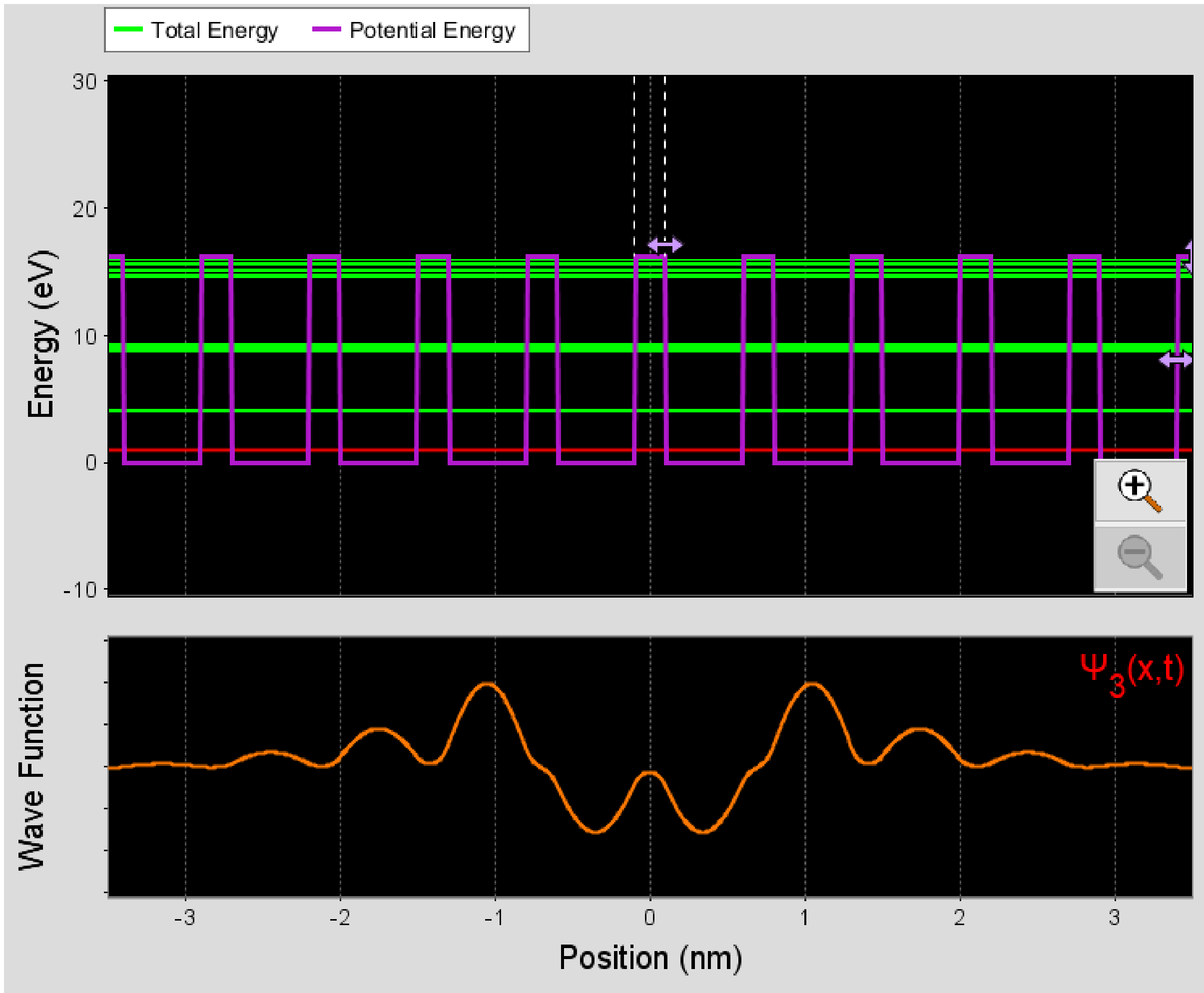


https://www.st-andrews.ac.uk/physics/quvis/

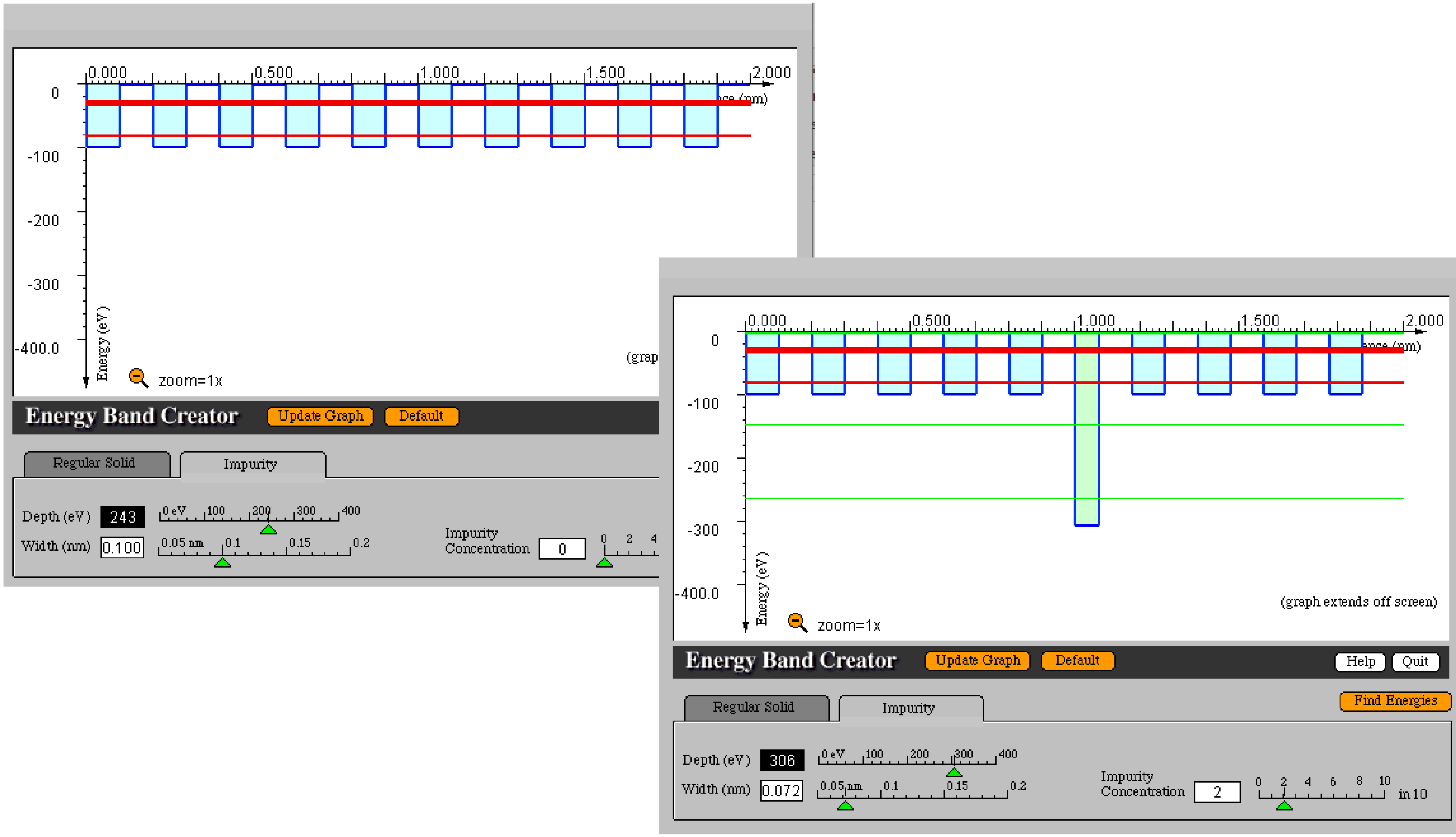
How do the energies and wave functions change when we have two wells.



With 10 wells we see the energy band and gap structure

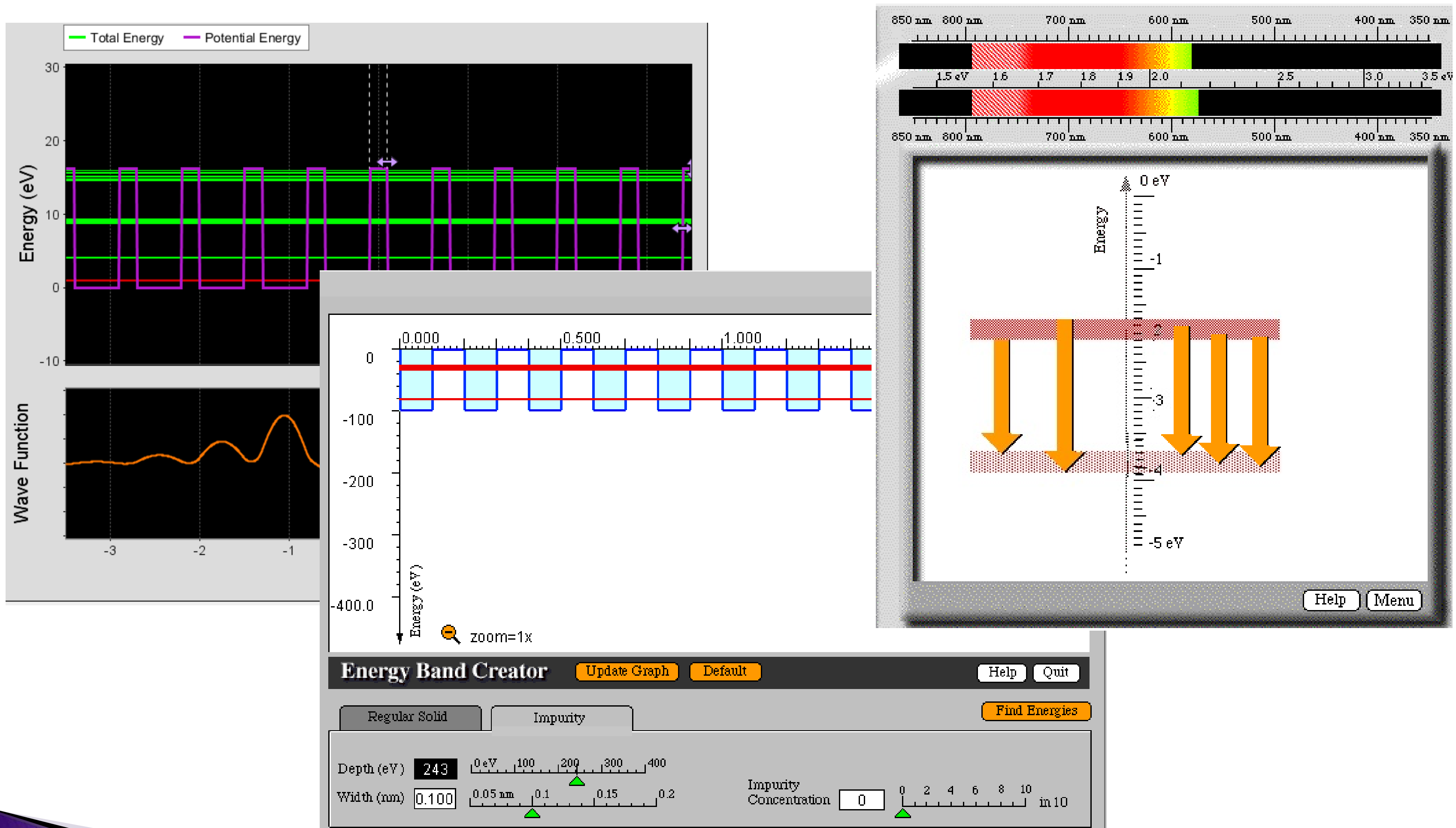


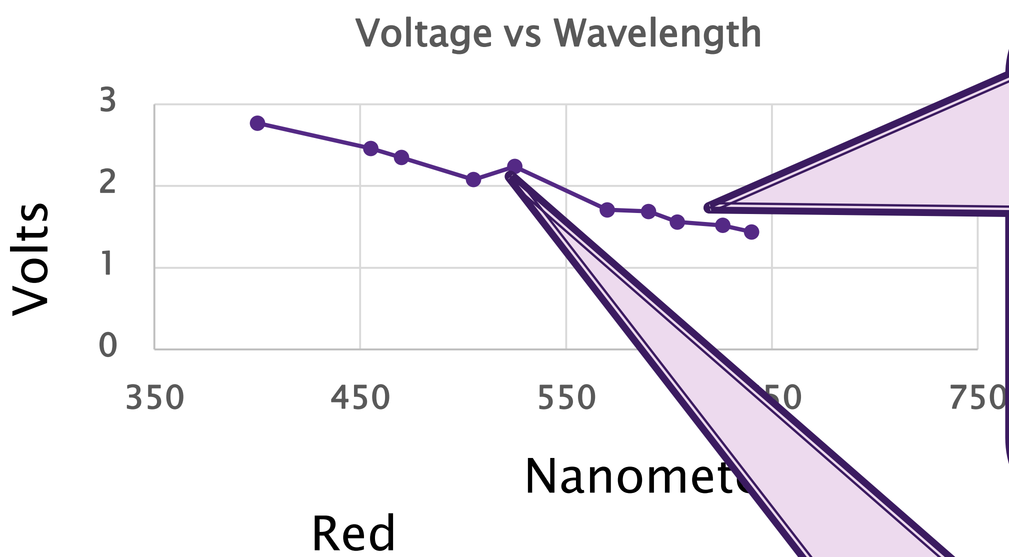
Extend to more wells & an impurity



https://www.phys.ksu.edu/ksuper/research/vqm/

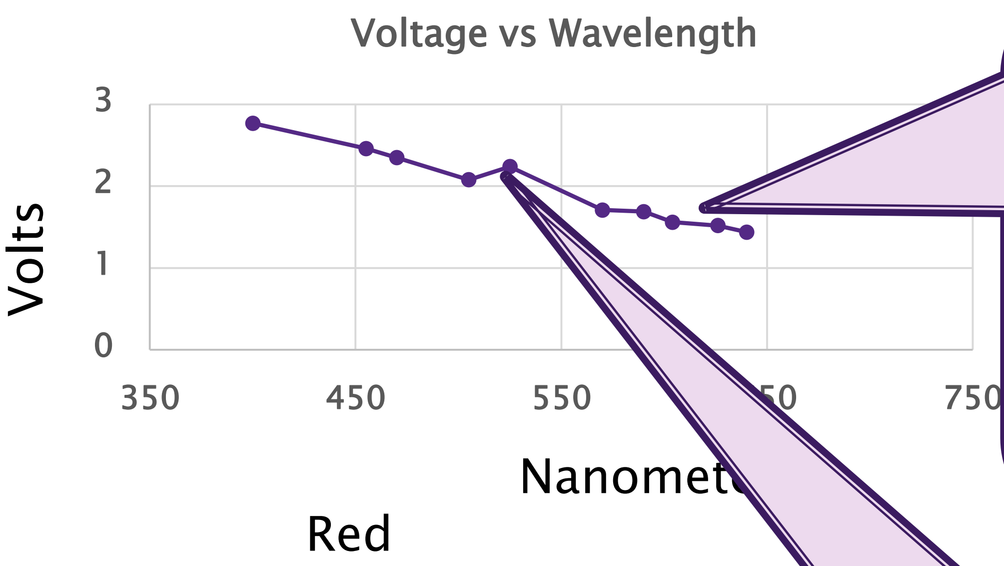
With knowledge of bands & gaps go to emission of light.





Why does the graph show almost straight line behavior?

Why does this LED seem to deviate from the straight line?



The relation between the energy gap in solids and energy of light emitted explains the straight line behavior.

But we do not yet have an explanation for why this LED deviates from the straight line.

Modeling the Bright Green LED

My personal thinking about this (part 1)

Use my existing knowledge applied to this issue

- My model of light emission from an LED is
  - Energy bands & gaps explain the spectra of the LED
- This LED does not fit the model, so
- The wavelength label on the device is wrong.
- The light is not emitted at 525 nm.

But …

Spectra of LEDs from the device

Observation disagrees with my reasoning . The spectrum is centered on 525 nm.

Photo: Udine (Italy) Physics Education Research Group

My personal thinking about this (part 1)

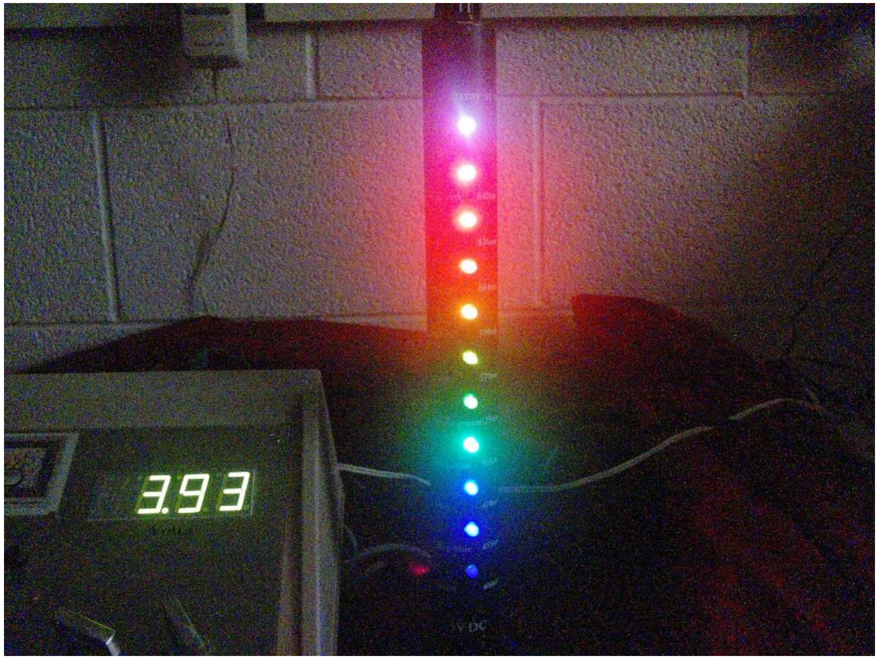
Use my existing knowledge applied to this issue

- My model of light emission from an LED iis
  - Energy bands & gaps explain the spectra of the LED
- This LED does not fit the model, so
- The wavelength label on the device is wrong.
- The light is not emitted at 525 nm.

I needed to re-think my reasoning

An important clue

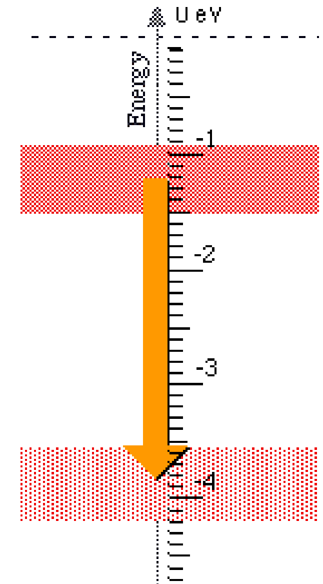
The bright green, white and blue LEDs all turn on at about the same voltage (~3 volts)

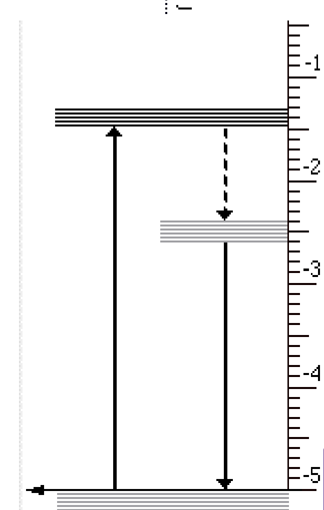


https://youtu.be/r7XFx1rY8fA

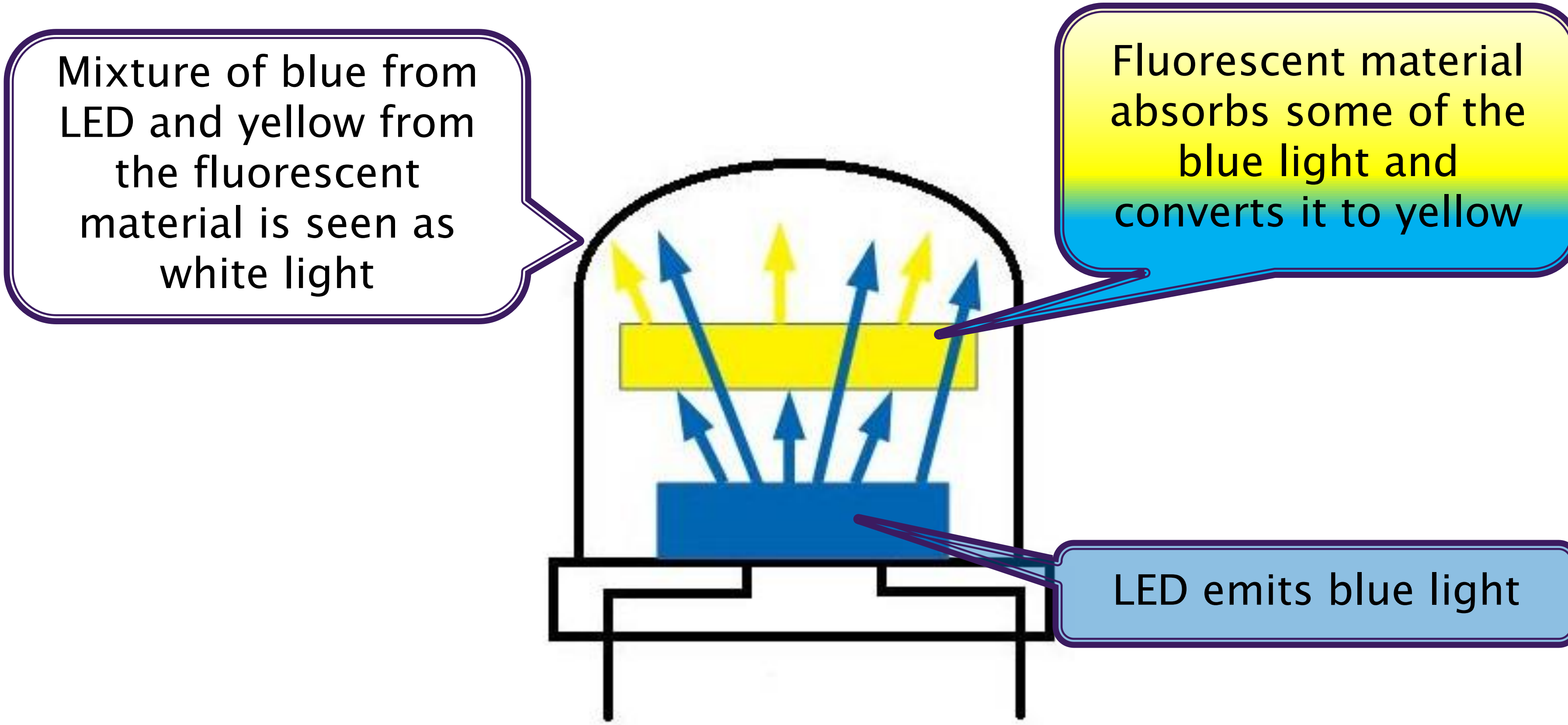
Important Knowledge

- In a separate unit students explore the white LED
- Energy bands & gaps model alone does not explain white LEDs
  - Threshold voltage is approximately equal to blue threshold voltage
- White LEDs include fluorescence in the light emission.





White LED



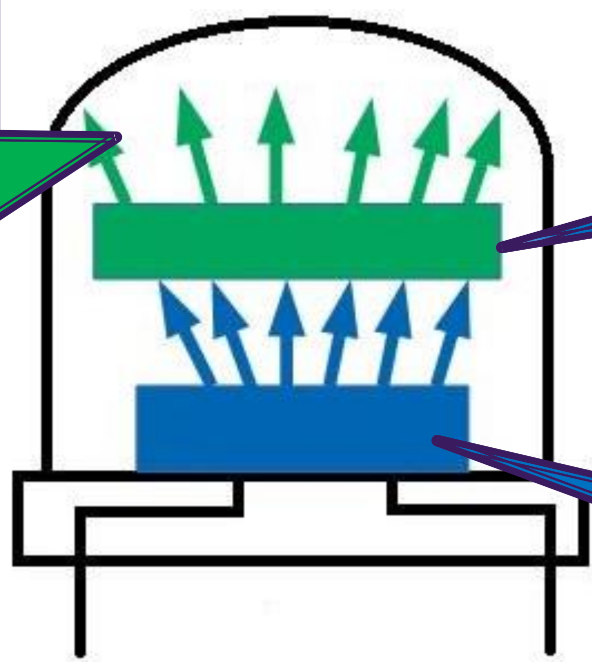
The white LED turns on at the same voltage as the blue LED because it has only a blue LED in it.

My personal thinking about this (part 2)

My more careful thoughts

- The threshold voltage of bright green LED is about equal to the threshold voltage for white and blue LEDs
- Bright green LEDs are fundamentally different from the energy band & gap model
- They are similar to the white LED that uses a blue LED AND fluorescence.
- The bright green LED must also use a blue LED and fluorescence.

Bright Green LED

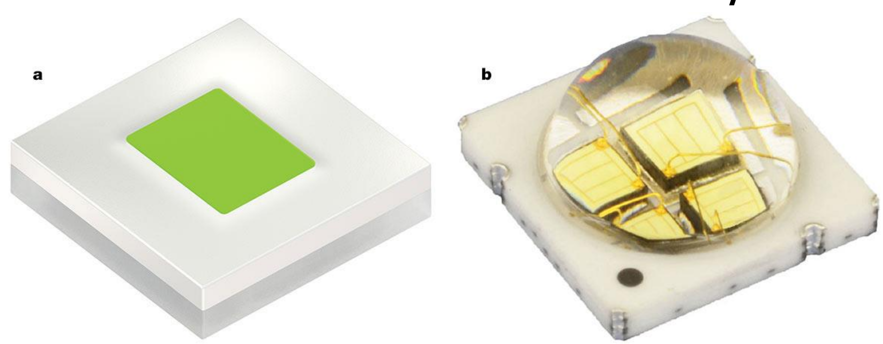


The bright green LED is constructed very similarly to the white LED. It also has only a blue LED in it.

An energy gap in the green is difficult to achieve.

- [There has been] a **conspicuous shortage of affordable and efficient solid-state green light emitters.**

- [Now, some] manufacturers are offering **bright green bandgap emission LEDs** …
  - Faiz Rahman 2019 The Shrinking Green Gap: Trends in Solid-State Green Emitters *Photonic Spectra* **53** 52-59



Osram Optosemiconductors.

Determining Planck's constant with LEDs – What could possibly go wrong?

- Dean Zollman & Ian Bearden, submitted for publication

Brief Summary

- Simple experiments with LEDs can provide hands-on activities related to quantum physics
- Attempting to explain the results of the experiment, students can use
  - An empirical model based energy levels in atoms and solids
  - A visual (or mathematical) model base on wave functions
- Students can also understand anomalies that do not quite fit the models.

감사합니다

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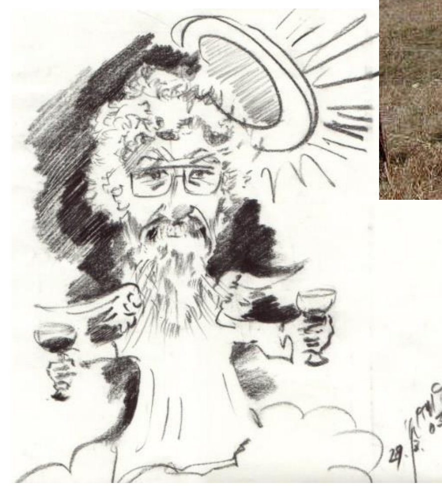

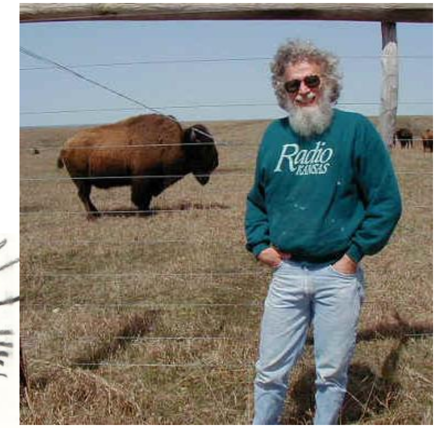

e-mail

Web

- Videos of LEDs
- https://youtu.be/Qt2KIFnrdkw
- https://youtu.be/uy-xTadGobY
- https://youtu.be/r7XFx1rY8fA
-
- Quantum related software & lessons
- https://www.phys.ksu.edu/ksuper/research/vqm/
- https://phet.colorado.edu
- https://www.st-andrews.ac.uk/physics/quvis/
-

- References
- The Shrinking Green Gap: Trends in Solid-State Green Emitters
- https://www.photonics.com/Articles/The_Shrinking_Green_Gap_Trends_in_Solid-State/a64221
- How LEDs Produce White Light
- http://www.photonstartechnology.com/learn/how_leds_produce_white_light

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