SOCIETY OF PHYSICS STUDENTS SOCK

Science Outreach Catalyst Kit

2001
Rainbow Room

Here's your SOCK—
SPS Outreach Catalyst Kit

SOCK # 1---The Rainbow Room

---Demonstrations and software for young and old about light answering questions like…

What wiggles and looks colorful?

See the Wave Slides presentation

Why are skies blue and sunsets red?

See the Coffee Creamer demonstration

How are Photons and Energy level diagrams related?
See the Visual Quantum Mechanics (VQM) CD

Contents of the SOCK- (SPS Outreach Catalyst Kit)

- Visual Quantum Mechanics (VQM) CD
- Disc with demo suggestions and colorful slides
- SOCK user guide text
- VQM bag with circuit board, LEDs, IR card, glowsticks, battery, polarizing films
- laser pointer (red)
- Slinky
- Rainbow glasses (10)
- Mag lite

About the User's Guide

There are two main sections to the users guide. The idea is to pick something you like and use the equipment and lessons in an outreach effort to facilitate hands-on learning about light.

- Rainbow Suite of Spectral Supplies
  - This is a group of demonstration ideas and resources about light that can be used with students at a variety of levels
- Visual Quantum Mechanics
  - This set of programs and demonstration equipment is just a sampling of what this group produces---It is especially useful for helping students to visualize how atoms produces light

Table of Contents

- Rainbow Suite
  - Introduction materials
  - Coffee Creamer Demo
  - Polarization Demo
  - Rainbow Room
  - Wave Slides
  - *Living with a Star* Booklet in pocket (Educator Resources from NASA)
- Visual Quantum Mechanics
  - Part A:Exploring Light Patterns (pages A1-A6)
  - Part B:Building Energy Models for Atoms (pp.B1-B5)
  - Part D:Adopting Energy Models to Explain (pp. D1-D8)

Who to contact

- If you would like more info about the supplies or their use you can email us at sps@sip.org (mention SOCKs in you subject field) or call the SPS office at 301-209-3007. We are especially interested in how they were used, to whom they were presented, and your impressions of their usefulness.

About SOCKs

- **SOCKs are part of an outreach effort developed by the Society of Physics Students (SPS) and supported, in part, by its associated physics honor society, Sigma Pi Sigma (ΣΠΣ). Both societies are affiliated with the American Institute of Physics (AIP).**
- **Special Thanks to**
  - The Kansas State University Physics Education Research Group, especially Dean Zollman, Kirsten Hogg and Kim Coy, and to Max Kurtz at Ztek Co.
  - The authors of *A New Model Course in Applied Quantum Physics*, Edward F. Redish, Richard N. Steinberg, Michael C. Wittmann and the Physics Education Research Group at the University of Maryland and their supporters, The National Science Foundation (NSF 9652877) and the Fund for the Improvement of Post Secondary Education (FIPSE 16B70186, 116B000300).
  - The members of the Northwestern State University of Louisiana chapter of the Society of Physics Students, initiators of the original Rainbow Room at the 2000 Zone 10 SPS meeting. Deserving special recognition are Kristen Russell, Michael Walker, Pepper Thiels, David Byrd, and especially Mark Lentz, who implemented the SOCKs idea as the first SPS summer intern in 2001.

Visual Quantum Mechanics
Complete Kit

Item	Supplier	Qty
circuit board w/ orange, red & green led	Bao Guangsen	1
T 1-3/4 lamp	Mouser Electronics	1
yellow led	Mouser Electronics	1
blue led	Jameco	1
infrared led	Mouser Electronics	1
trimmer alignment tool	Mouser Electronics	1
Assortment of light sticks	Gee Sales	
UV detecting beads	Educational Innovation	5
glow-in-the-dark ball	Oriental Trading Co.	1
glow-in-the-dark ball	Oriental Trading Co.	1
IR Detector Card	Radio Shack	1

Educational Innovations, Inc.
362 Main Avenue
Norwalk, CT 06851
Tel: 203-229-0730
FAX: 203-229-0740
www.teachersource.com

Gee Sales
1114 N. Melody Circle
Chandler, AZ, 85225
Tel: 888-894-8879
Fax: 480-857-3109
www.geesales.com

Bao Guangsen
Nanjing Baihua Opto-Electronic
Tian Shan Road 39
Nanjing Jians 99 21000-8
China
Tel: 0086-25-7712251
Fax: 0086-25-7711256

Jameco Electronics
1355 Shoreway Road
Belmont, CA 94002
Tel: 1-650-592-8097
Fax: 1-650-592-2503
Toll Free Tel: 1-800-831-4242
Fax: 1-800-237-6948
www.jameco.com

Mouser Electronics
PO Box 714,
Mansfield, TX 76063-0714
Tel: 800-346-6873
www.mouser.com

Oriental Trading Co. Inc.
4206 S. 108th St..
Omaha, NE 68137-1215
Tel: 4402-331-5511
Toll-free: 800.875.8480
www.orientaltrading.com

Radio Shack
Local dealer or
www.radioshack.com

Other equipment vendor information:

1) Diffraction Grating Rainbow Glasses

Rainbow Symphony
6060 Canby Ave.
Reseda, CA 91335
(818) 708-8400

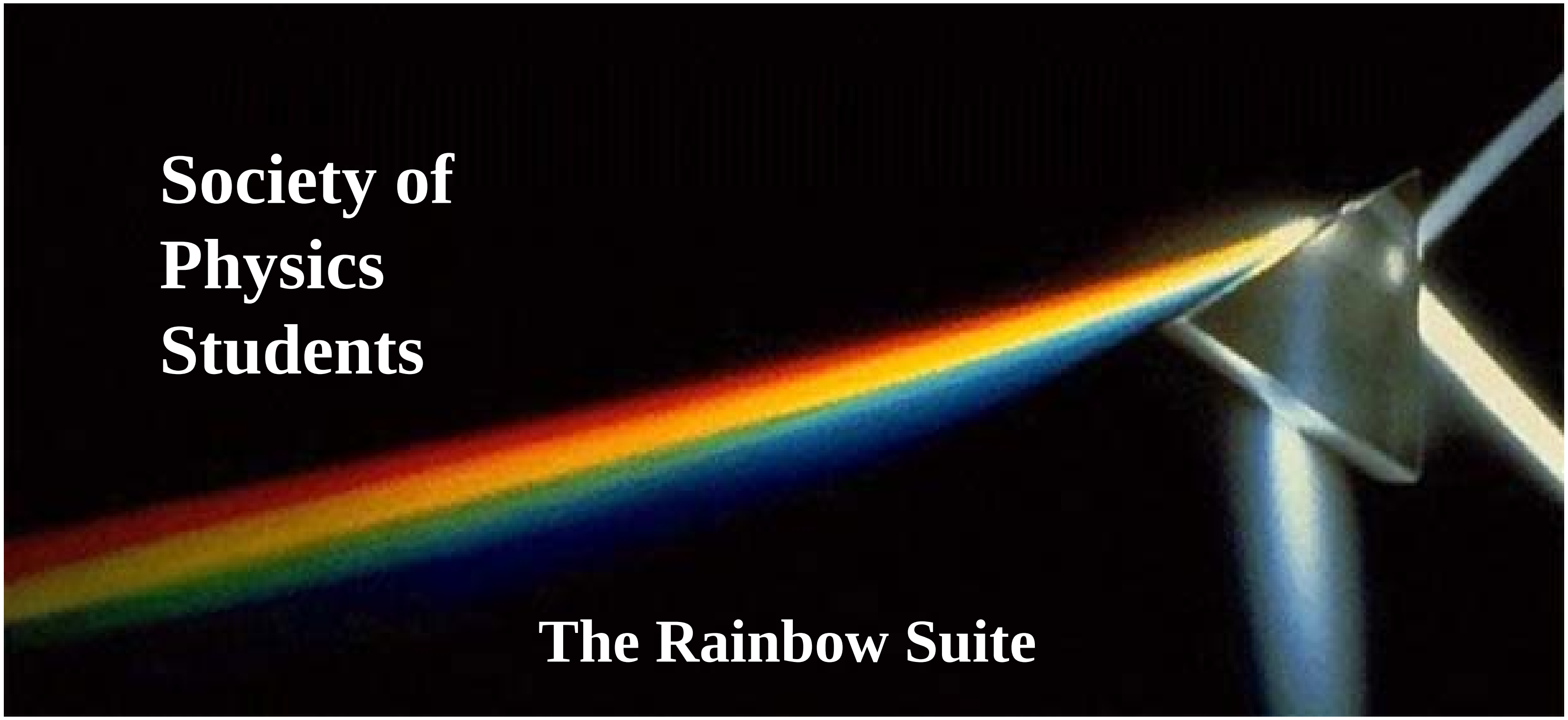
2) Keychain Lasers

TheLaserGuy.com
1502 Second Street
Seabrook, TX 77586
(877) 275-3220

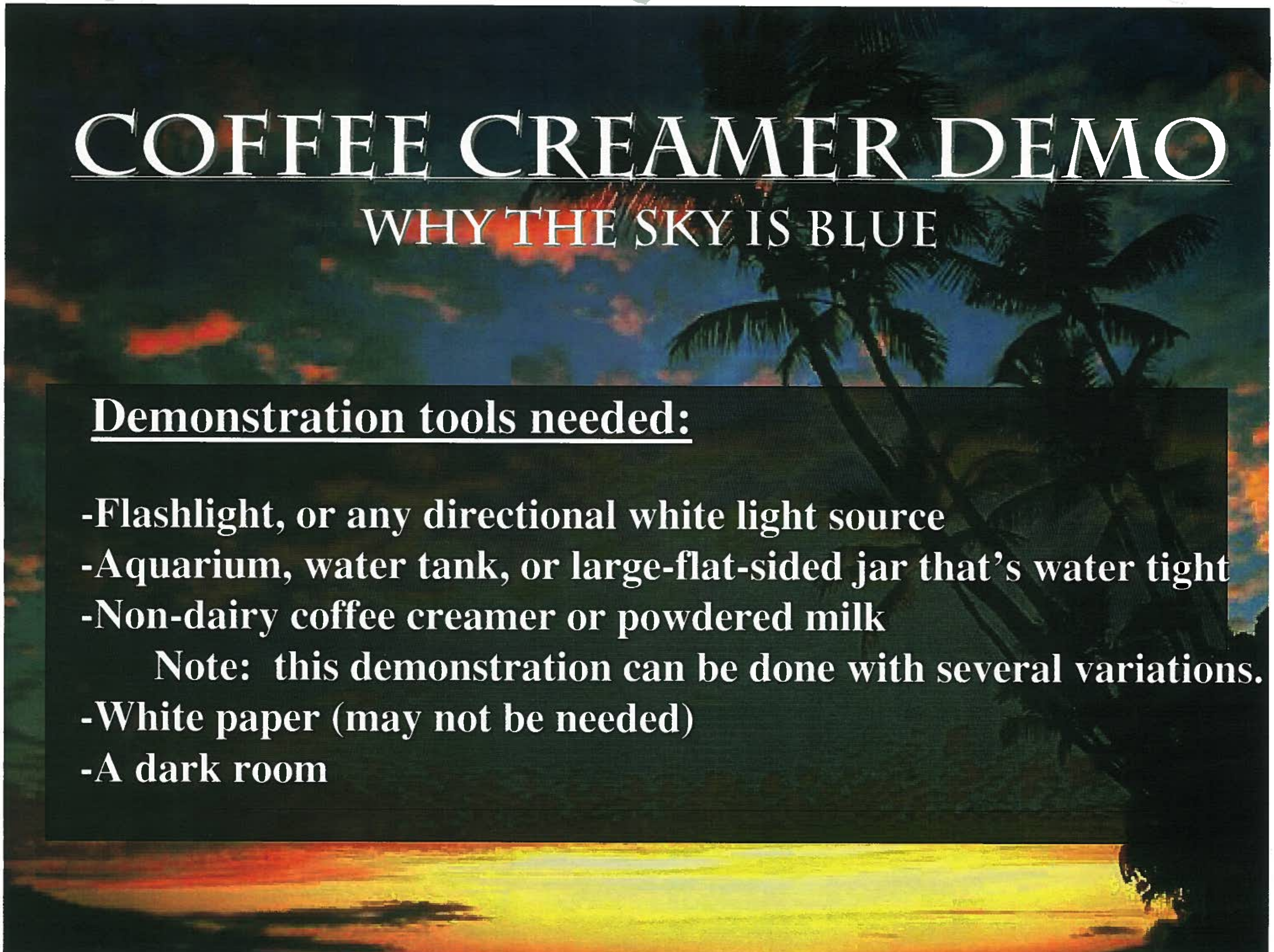
3) Polarizing sheets

Hotlights
133 West 19th St.
New York, N.Y. 10011
(212) 645-5295

We got the mini-maglites from Home Depot---they make a good point source of light, especially if the top is removed. There are many other distributors for these items that are relatively easy to locate on the web.

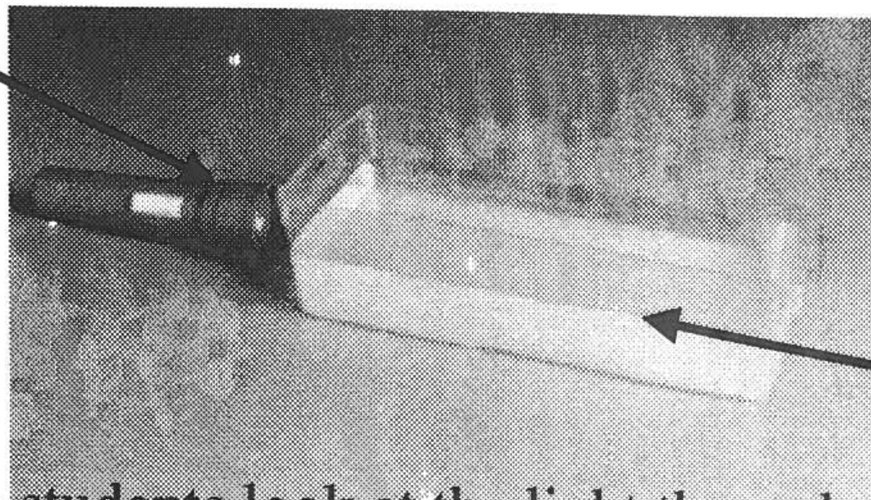


The pages in the print version of the User’s Guide are only a sampling of the materials contained on the SOCK User’s Guide CD. For more details about a particular demonstration or exercise, or for some advice about doing demonstrations, refer to the more complete version of the Rainbow Suite on the CD


COFFEE CREAMER DEMO
WHY THE SKY IS BLUE
Demonstration tools needed:
-Flashlight, or any directional white light source
-Aquarium, water tank, or large-flat-sided jar that's water tight
-Non-dairy coffee creamer or powdered milk
Note: this demonstration can be done with several variations.
-White paper (may not be needed)
-A dark room

BASIC SETUP

White light source



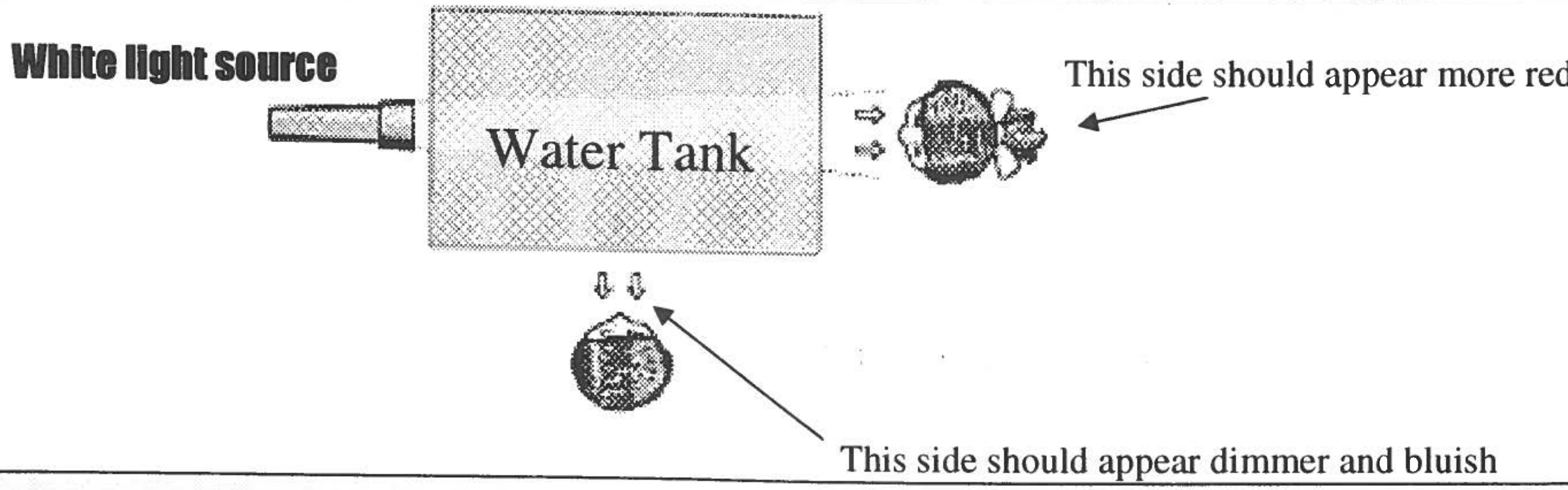
Plain water

Have the students look at the light through the water and notice that it still looks white.

As they continue to look through the water at the source, begin to slowly poor the creamer through out the water, simulating molecules in the atmosphere, if you put too much, the light source will be completely blocked. (It's recommended that this demonstration be practiced.)

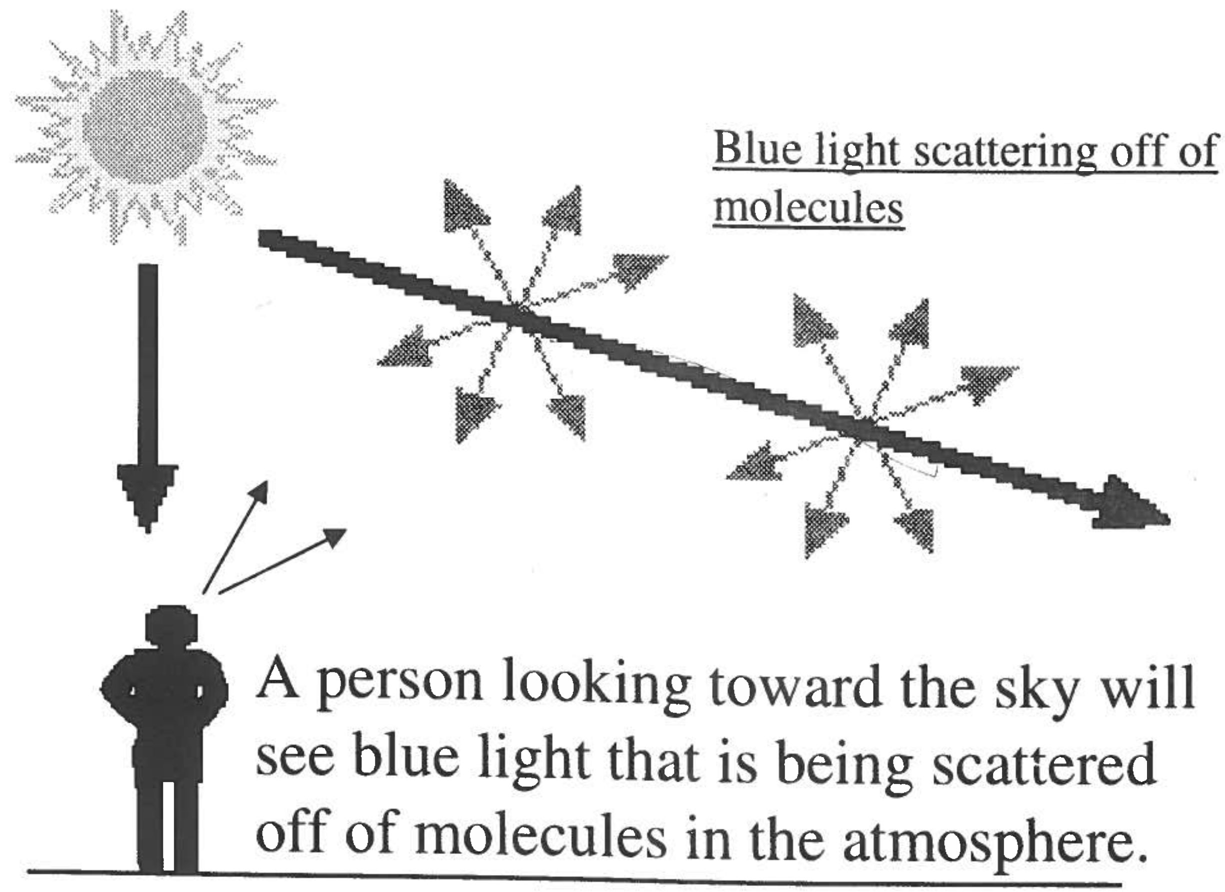
Look at the beam from the side of the tank and then from the end of the tank. You can also let the light project onto a white card, which you hold at the end of the tank. From the side, the beam looks bluish-white; from the end, it looks yellow-orange. If you have added enough creamer to the water, you will be able to see the color of the beam change from blue-white to yellow-orange along the length of the beam .

Students standing at the far end of the tank should actually be able to watch the light source turn more reddish-orange in color as the creamer is added.



Students standing sides of the tank should begin to see a blush color emerging. It may be helpful to use a white piece of paper as a sort of view screen along the sides to see the bluish tint.

A clear cloudless day-time sky is blue because <u>molecules</u> in the atmosphere scatter blue light from the sun at larger angles than they scatter red light.



When we look towards the sun at sunset we see red and orange colors because the blue light has been scattered at right angles, away from the line of sight toward the sun.

POLARIZATION OF LIGHT

Ideas for Demonstrations and materials needed:

Horizontally and vertically polarized waves:

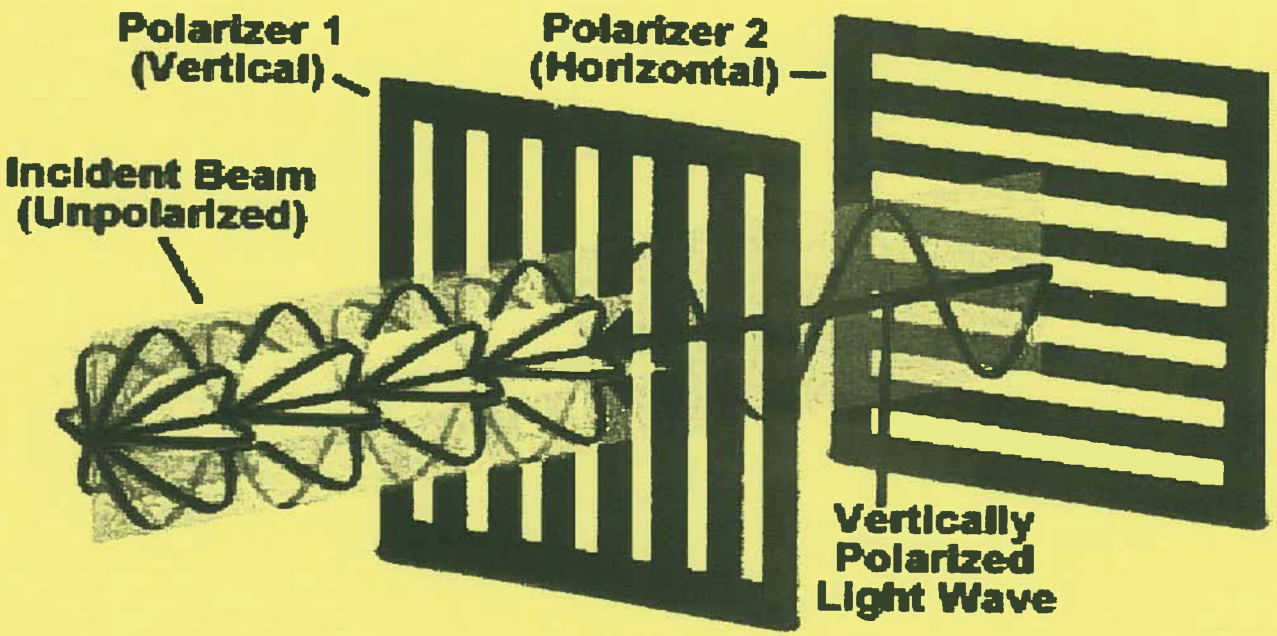
-slinky and poster board
-available graphics

Showing that light is a polarized wave:

-light source and polarizing plastic sheets
*clear bottle of corn syrup, isn't necessary, but makes for a colorful display of polarization.

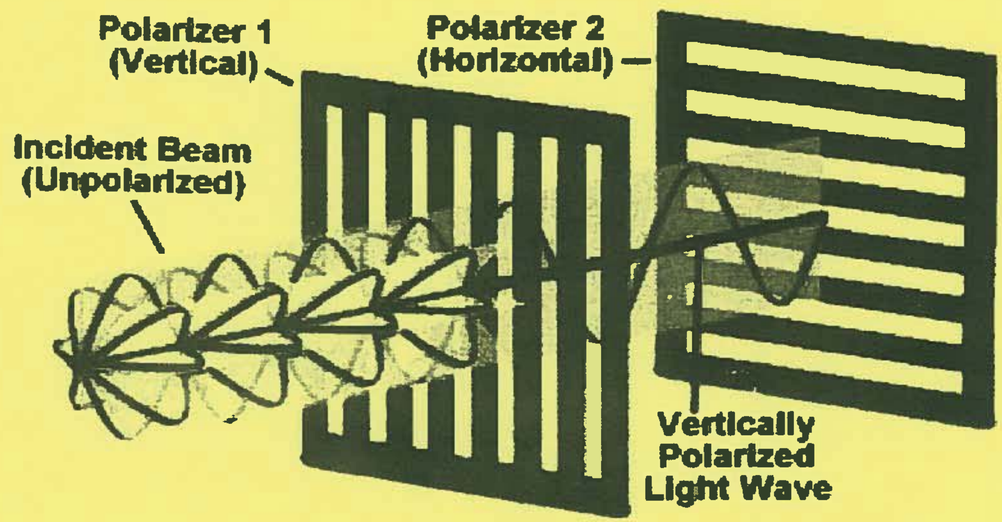
The slinky can be used to demonstrate a horizontally or vertically polarized wave. Cylinders of rolled up poster board can be used as either horizontal or vertical polarizers. This is a large scale demonstration that can be interactive for the students. Polarization can be a difficult topic to discuss and for students to grasp. Using large scale demonstrations in conjunction with the smaller scale polarizing sheets can be quite helpful. Also using graphics to represent what happens can be useful.

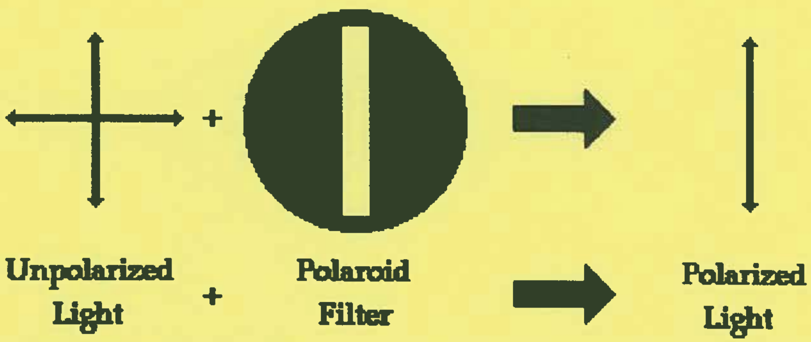
Light Passing Through Crossed Polarizers

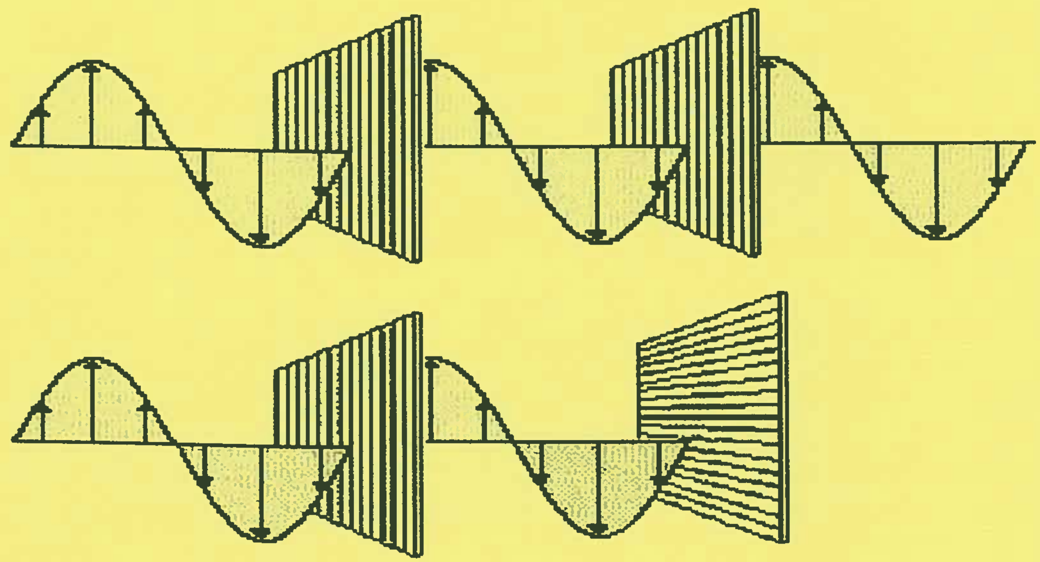


Here are some graphics that might be useful….

Light Passing Through Crossed Polarizers







Relationship Between Long-Chain Molecule Orientation and the Orientation of the Polarization Axis

The Rainbow Room

This can be a feature of any science meeting or outreach event. Find a room that can be darkened and set up as many kinds of sources as you can find. Bring students into the room individually or in groups and have them put on their rainbow glasses. It can be a time for free exploration, group discussions or even a more formal lesson such as Spectral Scavenger Hunt.

Rainbow Room Light Source Ideas

- Sources from SOCK
  - Laser
  - Glowsticks
  - Glow-in-the-dark balls
  - Maglight
  - Circuit board sources
- Other suggested sources (not included in SOCK)
  - Black lights
  - vapor tubes
  - Incandescent bulbs
  - Florescent lamps
  - Fluorescent liquids (highliters solution, detergent finger painting)
  - Plasma-ball
  - Spark generators

Spectral Scavenger Hunt—V2

Can you find a small light source with a rainbow that is mostly red with only a little yellow and green?

What kind of spectrum does a regular light bulb have?

a) a full rainbow with all the colors
b) a few colors, separated by dark areas
c) not really a rainbow but only red
d) a rainbow with mostly just blues and greens

Cut a thin slit (1/4" x 2") in a piece of thick paper and view a fluorescent light with your glasses on through the slit. You should see some colors in the rainbow are brighter than others. Which ones are brighter? How do they compare to the spectrum of Mercury as shown in your textbook or in the VQM software? What do you think this means about what is contained inside a fluorescent lamp?

Student question: What is light?

Often given teacher/textbook answers:

...electromagnetic radiation produced when electrons jump from one energy level to another lower level...
...transverse waves of oscillating electric and magnetic fields...
...quanta of energy that propagate at 186,000 miles per second...
...the electromagnetic spectrum—ROYGBIV, Ultra-violet, Infrared, microwaves, X-rays, radio waves, gamma rays, television...
...a form of energy that is massless and is emitted anytime charged particles are accelerated...
...the bosonic mediator of the electromagnetic interaction analogous to the graviton or the gluon, blah, blah, blah...

Better teacher response: What is light like? ...What is light not like?

Newton: Light is like particles…	Supporting evidence:
Young, Fresnel, Huygens, Maxwell: No, Light is like waves…	Supporting evidence:
Planck, Einstein, Lenard: But light is like particles, too…	Supporting evidence:
Bohr: Light is either like particles or waves, but not both at the same time…	Supporting evidence:
21st century scientist: (What would you sav?)	Supporting evidence:

Types of Waves

-For clarity, it may be necessary to distinguish the type of wave that the slinky is being used to demonstrate. A student might think that every type of slinky wave represents a light wave. But depending on the age group, this might be too much information to address.

Longitudinal Wave

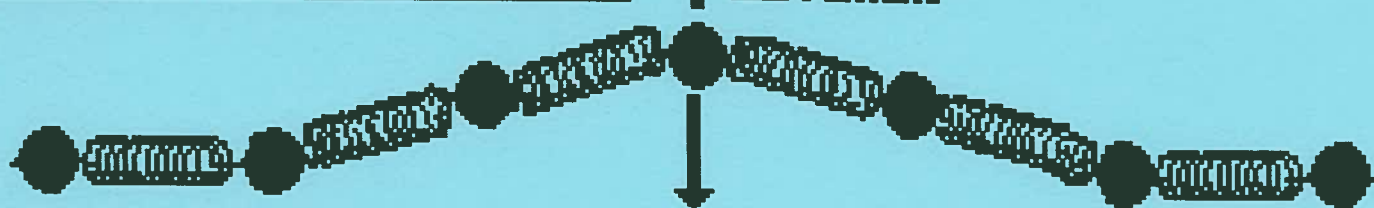
Particle Movement

Sound wave/slinky analogy

Transverse Wave

Light wave/Slinky analogy

Particle Movement



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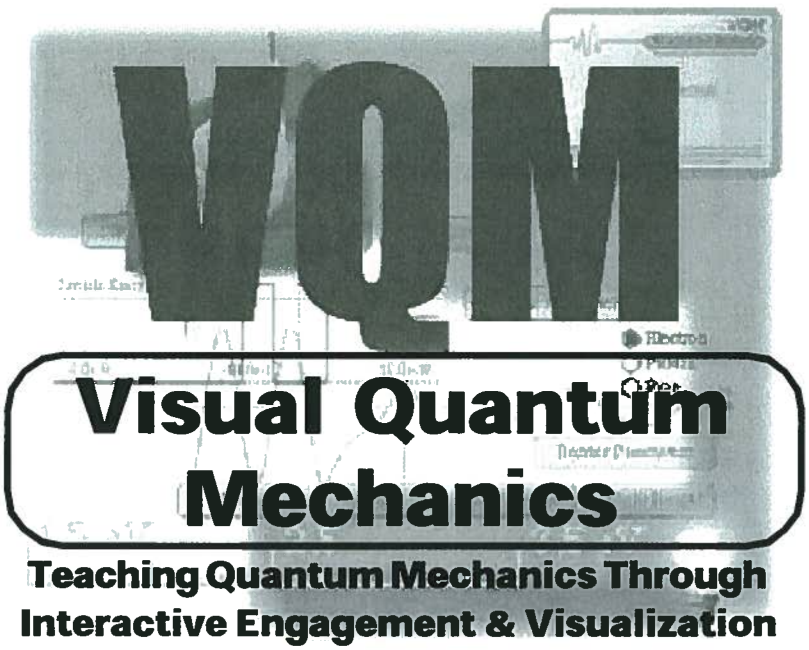
Coming Soon...



The Visual Quantum Mechanics (VQM) project has created a series of teaching/learning units to introduce quantum physics to high school students and college students with little background in science or mathematics.

In the attached sampler you will see parts of a few lessons for teaching quantum physics to this group. Much of the learning is related to simple devices such as the light emitting diode (LED), gas lamps, and chemical light sticks. This sampler does not contain all of the activities which students would do. Instead you will experience a few of the highlights.

Instructional Units

Solids & Light · Luminescence · Potential Energy Diagrams · Waves of Matter

Software

LED Constructor · Diffraction Suite · Quantum Motion · Quantum Tunneling
Spectroscopy Laboratory Suite · Wave Packet Explorer · Wave Function Sketcher
Probability Illustrator · Making Waves · Hydrogen Spectroscopy · Bound States
Energy Band Creator · Energy Diagram Explorer

Name: **Class:**

SOLIDS & LIGHT

Visual Quantum Mechanics

PART A
Exploring Light Patterns

> ***Goal***
> In this activity we will closely examine the light emitted by gas lamps, incandescent bulbs and LEDs. From these observations we will then attempt to build a conceptual model of light emission from atoms.

We will use a "photon" model for light as the basis for our investigations. In our investigations we will be particularly interested in the energy of the light emitted. Two factors --- brightness and color --- contribute in different ways to the energy of light.

Color

Atoms emit light in small packets of energy . These packets are called photons. Each individual photon contains an amount of energy that is related to its color. So, if we wish to discuss the energy of one of these photons, we need to know its color.

Low energy photons:	Infrared
	Red
	Orange
	Yellow
	Green
	Blue
	Violet
Higher energy photons:	Ultraviolet

$$E = hf$$

Each photon of visible light carries a very small amount of energy. This energy ranges from about 2.56×10^{-19} Joules for red light to 4.97×10^{-19} Joules for violet. Using these very small numbers is inconvenient, so we will use different units – the electron volt (eV). In these units, visible light energies range from about 1.6 eV (red) to 3.1 eV (violet) – much easier numbers to deal with.

 Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

Brightness

The brightness of the light is related to the number of photons emitted. A dim light will emit fewer photons than a bright light. Thus, we have two measures of energy — brightness and color. Because color is related to the light from each individual atom, we will concentrate on it.

Most light is composed of several different colors. To separate the colors we use a spectroscope.

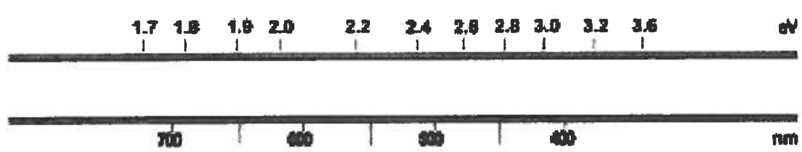
> Caution: (1) Some power supplies for gas tubes have exposed metal contacts. Because the gas lamp is a high voltage light source, do not touch the metal contacts that connect the gas tube to the power supply.
> (2) Never look at the sun or a tanning lamp with a spectroscope. Eye damage may occur from brightness and from high energy ultraviolet photons.

On the following scales, draw the pattern of emitted light observed with the spectroscope for three gas lamps.[Hint] Use colored pencils or markers to indicate the position of color(s). Add a written description to record which colors seem bright

Light Patterns Emitted by Gas Lamps

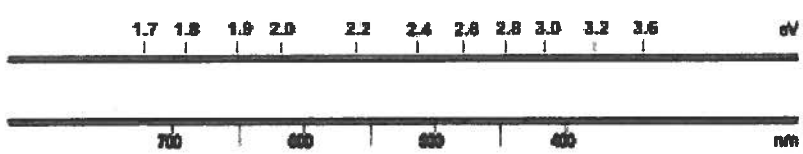
Hydrogen or ________________:

Color of the light without spectroscope__________



Helium or ____________________:

Color of the light without spectroscope__________

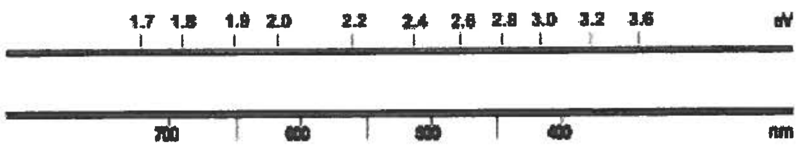


[Hint] To ensure that the light patterns are clearly visible, position the vertical slit of the spectrometer (found on the end with a screen) so that it is directly facing the light source and, if possible, hold the spectrometer less than a foot away from the light source. Dim the lights of the room so that the light patterns may be seen. The room, however, should be lighted enough for the energy scale to be seen.

A-2

Mercury or ________________:

Color of the light without spectroscope__________



In the table below record the color of light emitted by each gas lamp that is related to the greatest and least energy per photon.

Gas	Greatest Energy	Least Energy

? How can you tell which particular color of light emitted by each gas lamp results in the greatest number of photons emitted?

In the table below record the color(s) of light for which the greatest numbers of photons are emitted by each gas lamp.

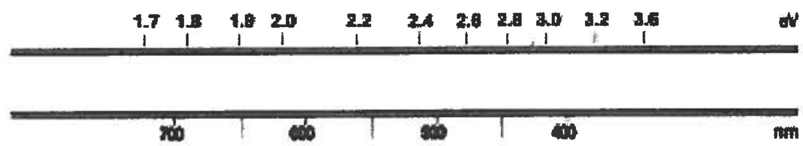
Gas	Greatest Number of Photons

A-3

Now use the spectroscope to observe the light pattern emitted by the clear incandescent lamp. Connect the incandescent lamp to the circuit provided. We will observe the light emitted by the incandescent lamp with the spectroscope when it is at maximum brightness.

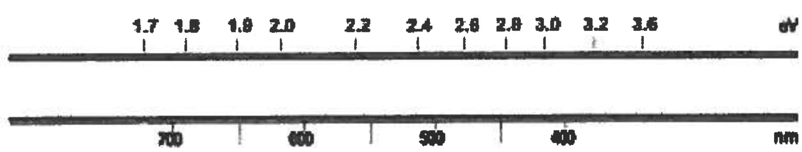
? On the following scale, draw the pattern of emitted light observed with the spectroscope for the incandescent lamp. Use colored pencils or markers to indicate the position of observed colors. Add a written description to indicate any colors that are brighter or dimmer than others do.

Light Emitted by the Clear Incandescent Lamp



Now look at the spectra of one colored incandescent lamp. Record the spectrum below and indicate the portion of the spectrum with the brightest light.

Color of light _______________.



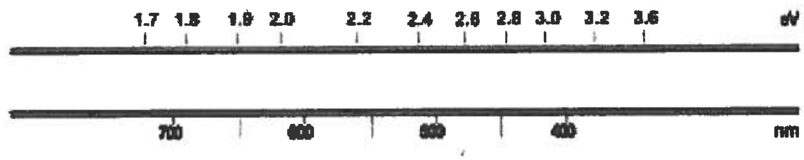
The pattern of light emitted by gas lamps is called a *discrete spectrum*. These light patterns appear as a limited number of bright lines of certain colors. The pattern of light observed for the incandescent lamp is called a ***continuous spectrum*** for its broad pattern of various colors with no dark regions.

Reduce the brightness of the incandescent lamp by using the potentiometer and the trimmer tool.

? What do you notice about the color of light that is emitted as you reduce the brightness to the point where light is barely visible?

We will now compare the spectrum emitted by the LED to those emitted by the gas lamps and the incandescent lamp. The best way to observe the light spectrum emitted by the LED is to look at the top of the LED down from above. Recall that the LED focuses light through the top.

Spectrum emitted by a ____________ LED.



Summarize the results of your observations of the LEDs by completing the table below.

LED	Color(s) of Light Observed	Energy (in eV) of Brightest Light Observed

A-5

Summarize the results of your observations of the light emitted by each source, their spectra and their physical characteristics by completing the table below with the differences and similarities among the three light sources.

Light Source	**Gas Lamps**	**Incandescent Lamps**	**LEDs**
Gas Lamps			
Incandescent Lamps			
LEDs			

Similarities

Differences

As we stated above, gas atoms have fewer interactions than atoms in solids. The spectra for gases show only a few energies while the spectra of solids contain a large number of energies. This observation is a hint that light emission from gases might be less complex than emission from solids. So, we will concentrate on gases in the next activity.

Name: Class:

SOLIDS & LIGHT

Visual Quantum Mechanics

PART B

Building Energy Models for Atoms

> ***Goal***
> You will use your observations of gas spectra to build a model of energies in an atom.

An electron in an atom loses energy equal to the difference between two energy values. The energy lost by the electron appears in the form of light. The energy difference determines the energy and, thus, the color of light emitted by the atom.

We will now use ***Spectroscopy Lab Suite*** to see how the spectra of light emitted by gases can help us understand more about the energies in an atom.

In ***Spectroscopy Lab Suite***, select *Emission* under *Gas Lamps*. Figure B-1 shows the screen that appears. In this program, we can

- Select a gas tube and drag it to the socket that is just above the lamps. Some of the light in the spectra for that gas will appear at the top of the screen.
- Add energy levels for an electron in a potential energy diagram by using the **Add Energy Level** button.
- Move the energy levels by selecting them at the left of the vertical energy scale and dragging them to the desired position.
- Create transitions (represented by vertical arrow) by selecting the electron's initial energy on the right of the energy scale. (It turns green.) Drag the transition arrow to the electron's final energy. When you reach the final energy, it will turn green.

 Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

- This process will enable you to create an energy level model of the light emitting process in an atom. From the results you will be able to learn about energy levels in atoms. A colored spectral line on the screen above the potential energy diagram will indicate the light emitted by the transition. If the light is not in the visible region of the spectrum, it will not appear on the screen.
- Move any of the energy levels after you have created a transition. Begin with hydrogen. Follow the procedure on the previous page to place the hydrogen gas tube in the socket. Some of the spectral lines for hydrogen will appear in the top spectrum.

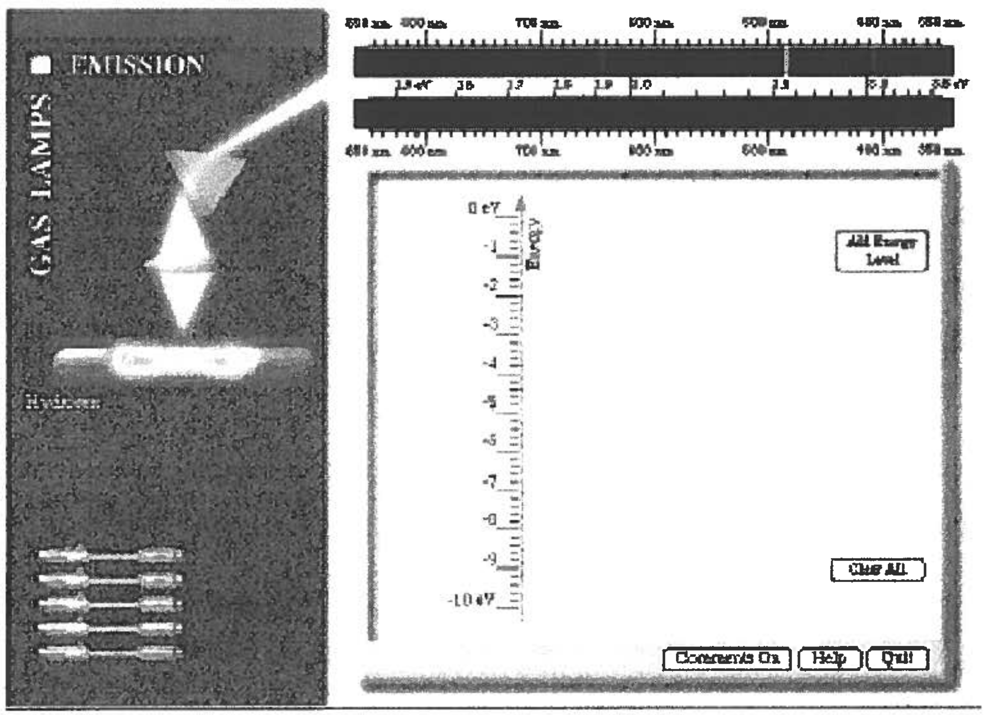


Figure B-1: ***Gas Lamp Spectroscopy*** **Computer Program**

Begin with hydrogen. Follow the procedure on the previous page to place the hydrogen gas tube in the socket. Some of the spectral lines for hydrogen will appear in the top spectrum.

Create energies and a transition that will match one of the spectral lines of hydrogen. The spectrum that you create appears on the lower spectrum.

Create and move energy levels until the bottom spectrum matches the spectrum of hydrogen as shown in the top spectrum.

Sketch the resulting energy level diagram for hydrogen in the space below.

? How many energy levels are needed to create these three spectral lines?

? How many electron transitions are needed to create these three spectral lines?

? What other, if any, possible electron transitions can take place with the energy levels illustrated on your screen?

Compare your energy diagram with the diagrams created by others.

? How are they similar?

? How are they different?

At this time none of the energy diagrams is more right or wrong than the others. We do not have enough information to distinguish exactly what transitions or initial and final energies occur in nature. Our model is limited by the knowledge that we have. Thus, all sets of energies and transitions that reproduce the spectrum are equally correct. (Scientists have more information to help distinguish the various possibilities, but that is not needed for our purposes.)

Advanced

You may like to refine your energy model of hydrogen by using the program Hydrogen Spectroscopy. It includes spectral lines from the infrared and ultraviolet regions.

We can create energy diagrams that provide all of the spectral lines rather easily. We need only a few energies to have sufficient transitions for all of the visible light. From this construction we conclude that an electron in an atom can have only a few energies. Otherwise we would see light of many more colors. This conclusion is somewhat surprising. When an electron moves in an atom, *it might seem* that the electron could have any one of many energies. But, nature does not behave that way. Instead electrons in atoms are limited to a very few discrete energies. We call these energies the **allowable** ones.

Repeat the steps to determine the energy levels and transitions necessary to produce the spectral lines emitted by another gas.

Sketch the resulting energy level diagram for the second gas in the space below.

? How is the energy level diagram for the second gas similar to the diagram for hydrogen?

? How are they different?

Up to this point, we have learned that light is produced when electrons make transitions in atoms. If they have high energy, they naturally lose it in the form of light as they move to a lower energy level. In a normal situation the electrons will be in a low energy level. They must first be given energy to attain high energies so that it can naturally lose that energy. An external energy source, such as electricity must supply that energy. This process is illustrated in Figure B-2.

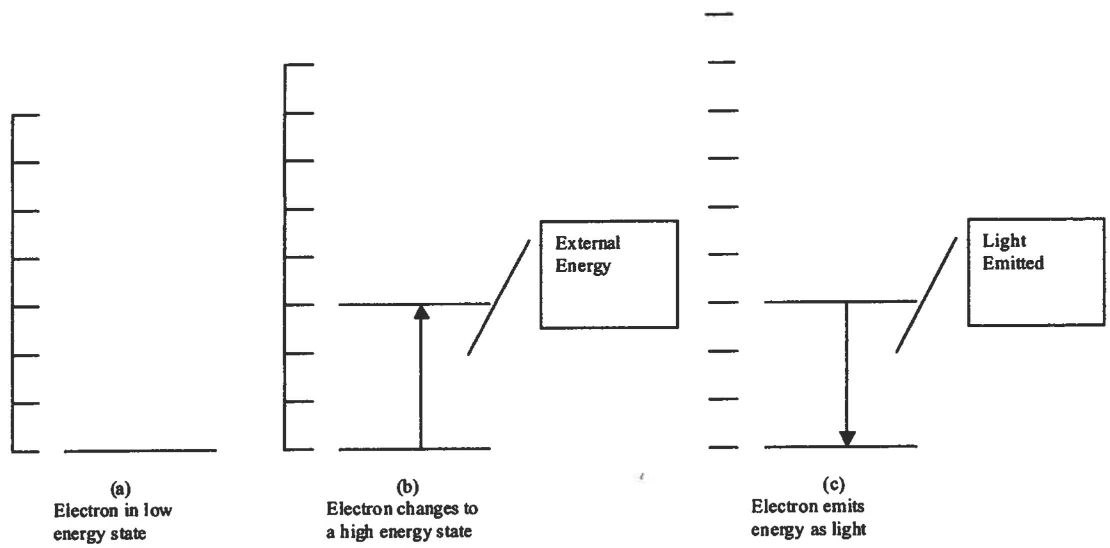


Figure B-2: Gain and Loss of Energy by Electrons in an Atom

The electrical properties of an atom uniquely determine what energies its electrons are allowed to have. So, even though the *Gas Lamp Spectroscopy* computer program allows you to adjust the energies available to the electrons, these energies are fixed at very specific values by the electrical properties of the atom.

Because the atoms of each of the elements have a unique set of energies, the light given off by a material can be used to determine the type of elements present. This property is used to learn about the composition of distant stars as well as substances on earth.

Name: Class:

SOLIDS & LIGHT

Visual Quantum Mechanics

PART D

Adopting Energy Models to Explain LEDs and Incandescent Lamps

> ***Goal***
> With the help of computer programs, we have been able to use the energy level diagram to explain the spectra emitted by gas lamps. We will now apply what we have learned to explain the spectra emitted by LEDs and incandescent lamps..

LEDs

Our study of gas spectra has led us to the conclusion that only certain energy levels can exist in a gas atom. Now, we wish to extend our investigation to solids so that we understand how LEDs emit light. As a first step we will explore how we might create a spectrum similar to that of an LED.

Open the *Emission* version of the *Gas Lamp Spectroscopy* computer program and place the unknown gas tube in the gas lamp socket.

When the unknown is in the socket, you can create your own spectrum by dragging the lines near the top of the screen. Edit the energy values for the computer-generated spectral lines so that the spectrum is similar to the spectrum of one LED that you previously observed.

Create an energy level diagram for an atom that could produce this spectrum.

In the space below sketch this energy level diagram.

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This exploration shows us that we could get a spectrum similar to that of an LED by having several closely spaced energy levels. When we look at the spectrum of an LED, we see a broad spectrum with no dark regions in it. So, atoms in an LED must have many energy states that are extremely close together. No real gas has the energy levels to create this type of spectrum. We can create it only on a computer with our "unknown" gas. So, we must look beyond gas atoms to explain the spectra of LEDs. This conclusion is not surprising because LEDs are made of small bits of solids.

Solids have many atoms that are close together and interact with each other. These interactions create very closely spaced energy levels. In addition to having energy levels which are very close together, a solid has an extremely large number of levels – literally billions and billions. Because of the large number and the close spacing we treat each group as a band of energy level. When you tried to match an LED spectrum with the *Emission Spectroscopy* program, you created something similar to an energy band with just a few levels. A solid may have several bands of energy. However, only two of the bands are involved in light emissions. (So, it works just like the model you created with closely spaced spectral lines.) The band with the highest energy contains electrons that cannot leave the solid but are not firmly attached to any atom. They can move throughout the solid. This freedom of motion allows these electrons to carry (or conduct) energy through the solid. So, we call this band the *conduction band*.

Electrons that have energies in the next lower band are bound to their respective atoms more strongly and are unable to break free from the atoms. This lower energy band is called the *valence band.* Electrons with these low energies have large negative values because they require more energy to escape their respective atoms.

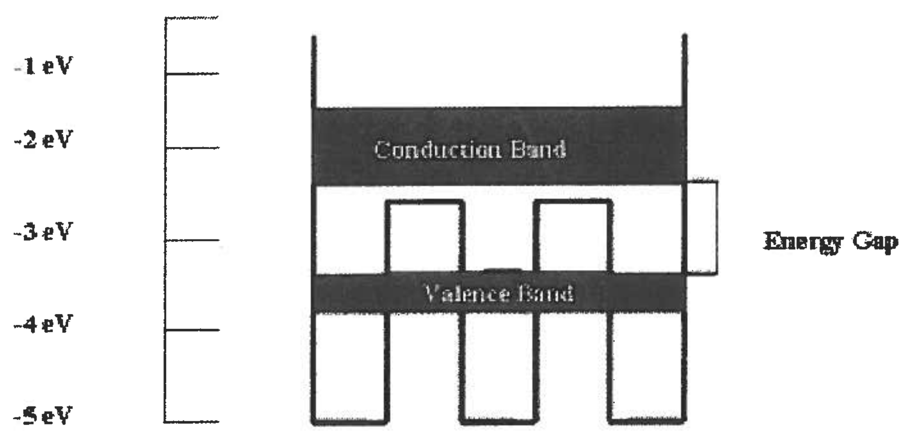

Figure D-1: Energy Diagram with a Very Large Number of Solid Atoms

The space between the conduction band and valence band has no allowed electron energies. This region is called the *energy gap*.

Now let's look at how energy bands are related to the spectra of LEDs.

In the ***Spectroscopy Lab Suite*** software package, select **LEDs** from the main menu. Figure D-2 illustrates how the screen should appear and provides basic instruction for using the program.

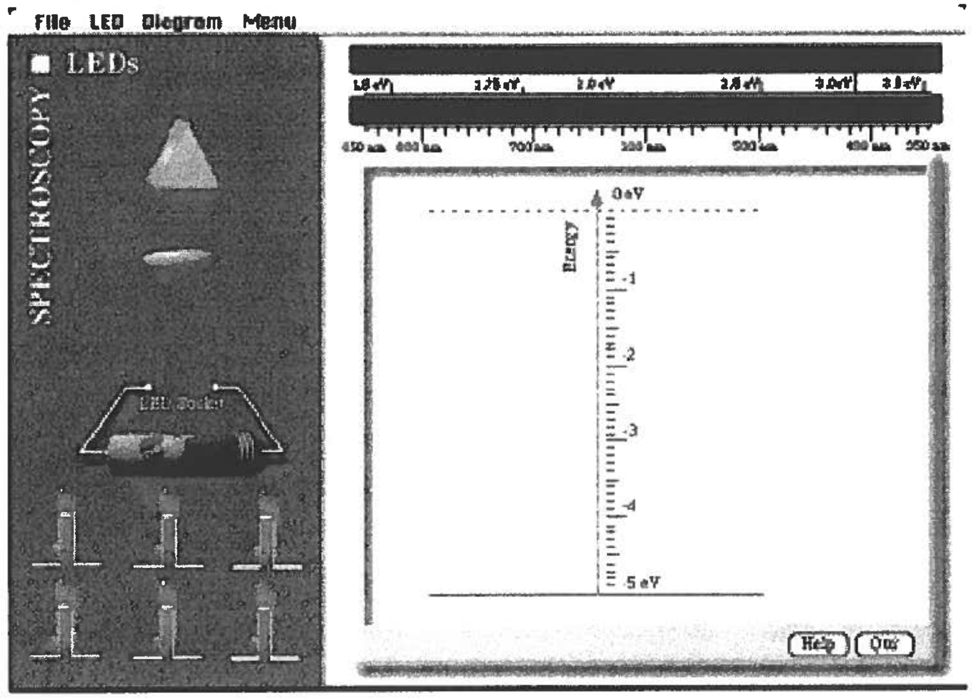

Figure D-2: *LED Spectroscopy* **Computer Program**

Drag an LED to the LED socket found on the left of the screen. The computer-generated spectrum emitted by the LED will appear on the top screen.

Click the **Add Conduction Band** button. A red rectangle that represents the conduction band for the LED should appear near the top of the energy scale.

Click on the **Add Valence Band** button. A faded-red rectangle that represents the valence band for the LED should now appear near the bottom of the energy scale.

The broad, orange vertical arrow represents the allowed transitions for electrons as they move from any energy in the conduction band to any energy level in the valence band. As these electrons make transitions, they emit energy in the form of light.

Place the cursor in the center of one of the bands. The band turns green and a hand symbol appears. You can now change the energy of the band by dragging it up and down.

Place the cursor on the top or bottom edges of one of the bands. The band turns green and up-down arrows appear. You can change the range of energies allowed in the band.

As you change the location of or range in a band, you will see the spectrum. Now manipulate the location and range of both energy bands until the spectra described by the energy level matches.

In the space below sketch the resulting energy band diagram and indicate the range of energy values (in eV) for each band and the resulting energy gap.

We are now able to apply energy diagrams to explain the spectra of LEDs. However, to be successful we need to extend the concept of individual allowed energies to allowed energy bands. The spectra emitted by LEDs is the result of electrons making transitions from a number of energy levels in the conduction band to a number of energy levels in the valence band. The electron transitions that are allowed can range from the highest energy level of the conduction band to anywhere between the lowest and highest energy levels of the valence band (See A on the left side of Figure D-3.). Other electronic transitions that are allowed can range from the lowest energy level of the conduction band to anywhere between the highest and lowest energy levels of the valence band (See B of Figure D-3.). These electronic transitions result in the emission of a broad continuous spectrum that is concentrated on a particular color (and thus energy) of light. The size of the energy gap in solids inside an LED determines the color of light emitted by the LED. Thus, if we know the spectra of light emitted by an LED we can predict its energy gap.

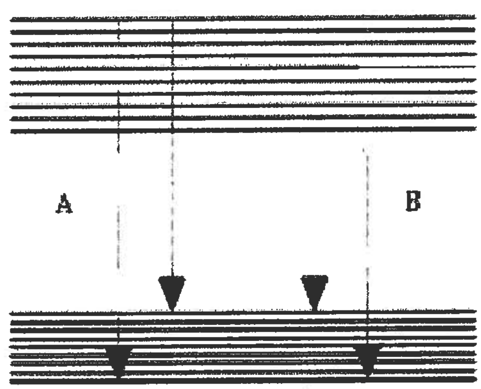

Figure D-3: Ranges of Allowed Transitions for a Solid that Makes Up an LED

Advanced

The model we developed with energy bands and gaps explained why we see a partial continuous spectrum for LEDs. They even allowed us to understand why we needed some minimal energy (voltage) to turn on each LED and why that energy depended on color. The model does not, however, explain how electrons get into the conduction band so they can emit light. To understand this process we must expand our model of the LED energy levels.

The LED chip consists of two solids – a material that has been supplied with donor atoms and the same material that has been supplied acceptor atoms. We will now use the *LED Constructor* computer program to understand how these two materials are combined to construct a simulation of an LED. Begin the process by opening the *LED Constructor* computer program.

In this program, we can:

- Select an LED and drag it to the power supply (LED socket).
- Create an energy band diagram for each of the two semiconductor blocks that make up each LED.
- Add donors or acceptors to each semiconductor block with a click of the mouse inside each block and thus create the LED chip.
- Control the voltage applied across the LED by moving the slider.

When the voltage is appropriate, transitions (represented by a vertical arrow) will occur and light will be emitted. A spectrum will appear below the energy scale.

Drag an LED to the LED socket. The energy bands that appear on both sides of the energy scale represent the bands and gap for materials associated with these LEDs.

Notice that the valence bands of both semiconductor materials are shaded darker than the conduction band. This shading indicates that the majority of electrons have energies associated with the valence bands. Electrons are naturally found in these bands because they seek the lowest possible energies. Also notice that energy of the energy gaps of both blocks are the same to represent that the LED is constructed of two blocks of the same semiconductor.

Now, click on the **Add Impurities** button. This places acceptors in the left block and donors in the right block.

? How does adding acceptors — atoms with fewer electrons — affect the energy bands of the left block?

? What is the effect on the energy bands of adding donor atoms to the right block?

? Do the sizes of the energy gaps for either semiconductor block change as donor or acceptor atoms are added?

? A material that has donor atoms has more electrons than one with acceptors. When these two materials are joined together, the electrons can move from one material to the other. Which way would you expect the electrons to move? Why?

Incandescent Lamps

The energy level model has successfully described the spectra emitted by gas lamps and LEDs. So, we will apply our model to explain the light emitted by incandescent lamps.

Open the *LED Spectroscopy* computer program and place any one of the LEDs in the socket.

Do not try to match the LED spectrum. Instead, use the program to construct an energy band diagram that would produce the spectrum emitted by an incandescent lamp when it is at maximum brightness.

? What is the range of energies (and colors) for the spectrum emitted by the incandescent lamp?

? How does the spectrum emitted by the incandescent lamp compare with the spectrum emitted by an LED?

In the space below sketch the resulting energy band diagram for your incandescent lamp.

? How does the energy band diagram for the light emitted by the incandescent lamp compare with the energy band diagram for an LED?

The energy band diagram that we just constructed represents the diagram for a "white" (mixture of all colors) light LED. Although incandescent lamps emit "white" light, typical LEDs only emit light of a single color. Incandescent lamps are also different from LEDs in that when the electrical energy supplied to the lamp is increased, the color (and energies) of light emitted by the tungsten filament (a solid) changes from the red region of the spectrum to "white" light as the filament heats up.

The energy diagram in Figure D-4 represents the bands and gaps for tungsten, the material in the filament of most incandescent lamps.

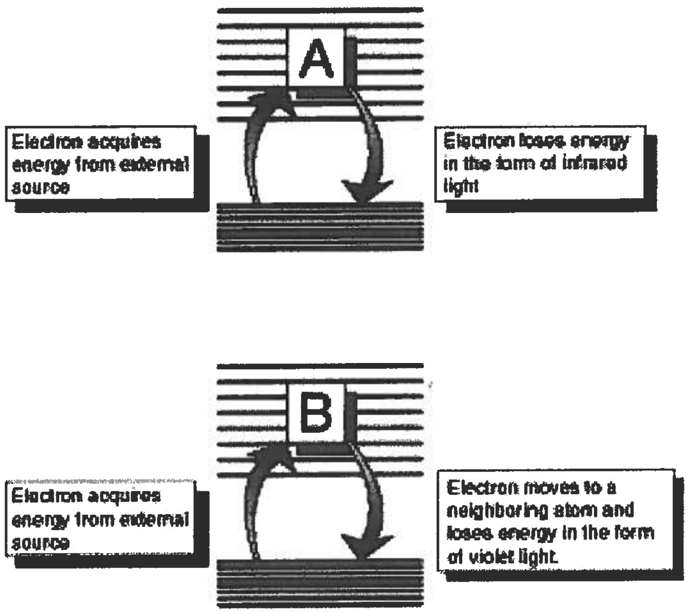

Figure D-4: Energy Band Diagram of an Incandescent Lamp Filament

Since electrons seek lower energy levels, the electrons of the tungsten filament have energies associated with the valence energy band. When the battery provides sufficient electrical energy, electrons in the valence band make the transition to an energy level of the conduction band. (See Figure D-4.) These electrons will then lose the energy they recently acquired when photons of light are emitted. As a result, the electrons make a transition back to the valence band of the filament. The light energy emitted can range from infrared to ultraviolet.

If the supplied energy is great enough, electrons from the valence band can make a transition to the highest energy level of the conduction band. These electrons make the transition back to the valence band by losing energy as photons of violet light (3.1 eV). Since enough electrical energy is being supplied to move electrons from the valence band to the highest energy level of the conduction band, the energy is more than sufficient for electrons to make a transition from the valence band to any energy level found between the lowest and highest energy levels of the conduction band. As a result, photons of light ranging from red (1.6 eV) to violet (3.1 eV) are also emitted.

When the energy supplied to the incandescent lamp is low, the color of the light has a large red component. At low voltages many of the electrons will receive just enough energy to reach lower energies in the conduction band. So, they can only emit light in the low energy end of the spectrum. Infrared light, which has a lower energy than visible light, is also emitted. This energy causes the lamp to be hot.

As the energy increases, the color of the light becomes "white." The number of transitions that result in the release of photons in the middle or high energy end of the visible spectrum increases. Thus, the color of the light shifts from reddish to white.