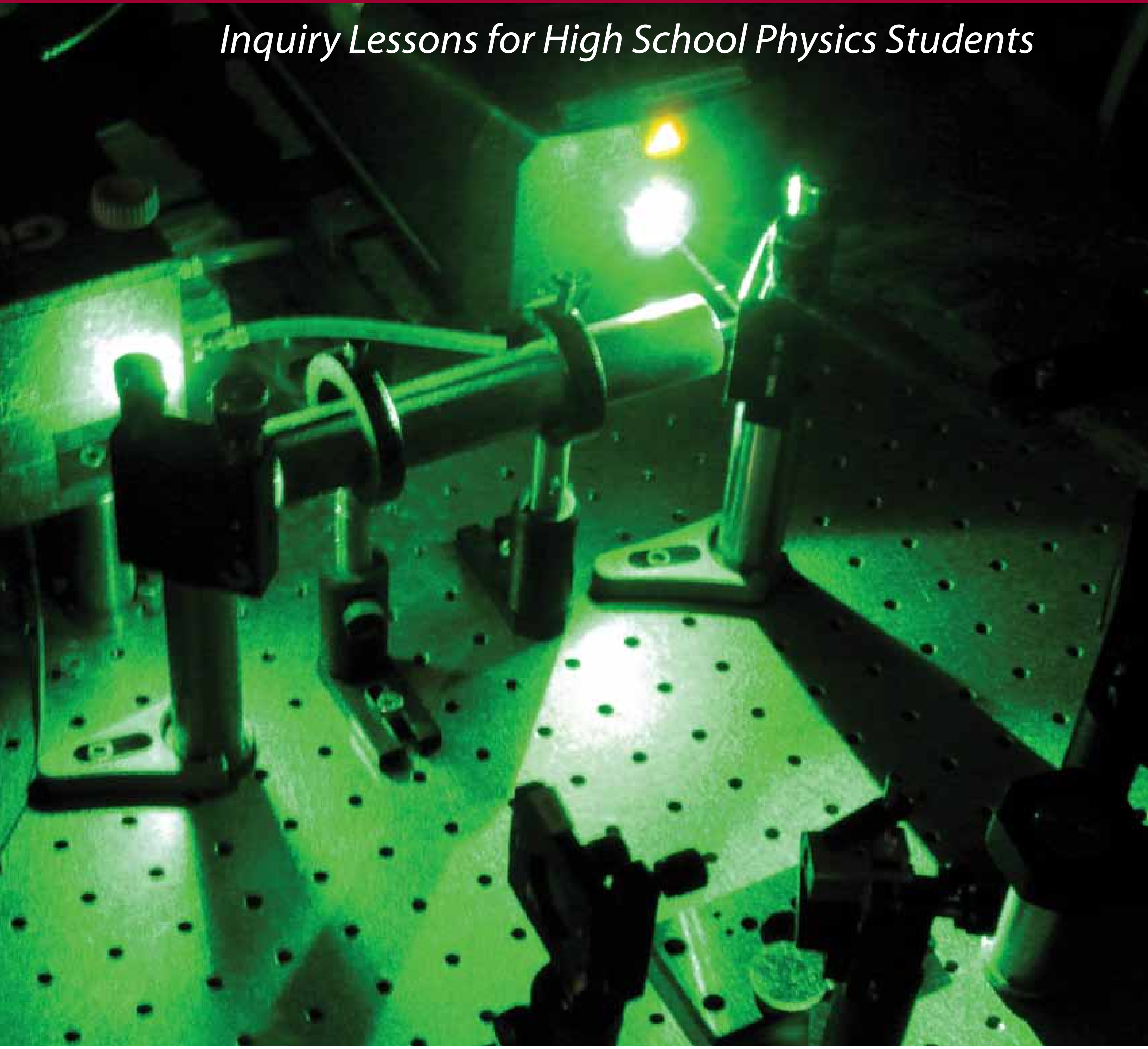
Student Edition

The Physics of LASERs

Inquiry Lessons for High School Physics Students



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Cover Image: *Green diode-pumped solid state laser pumping a Titanium Sapphire laser.* ***Image courtesy of:*** *Sara DeSavage and Kyle Gordon, Laboratory of F.A. Narducci, Naval Air Systems Command, Patuxent River, Md*

Lesson 1. What's Special about LASER Light?

Introductory Questions

- Where do you see lasers in your everyday experiences?
- Lasers have many applications because laser light has special properties. What do you think these properties are?

Discuss your ideas with your group and write down your group's ideas. Be prepared to share your group's ideas with the class.

Goal

By the end of this lesson you should be able to describe the properties of laser light that make it different from light produced by other light sources, along with supporting observations made during this lesson.

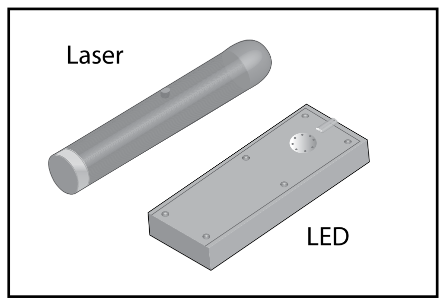
Safety

Never look directly into the laser beam. Never look at laser light reflected off of a highly reflective surface like a mirror or a ring. Instead, view a reflection of the beam from a piece of paper or a wall. Viewing laser light directly can burn your eye, causing permanent damage.

A. What is special about the color of laser light?

Materials list

- red LED (light emitting diode)
- white LED
- laser pointer
- diffraction grating (in slide mount)
- 1 sheet of white paper (8.5" x 11")



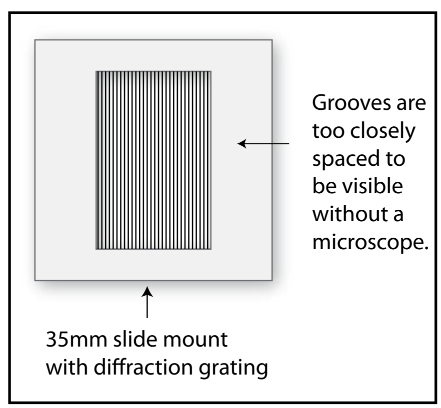


Image credit: Nancy Bennett-Karasik, @ American Physical Society

1. With your group discuss what you think is special about the color of laser light. Be ready to share your group's ideas with the class. By the end of *Part A*, you should be able to answer this question with supporting observations.

2. Find the slide that has clear plastic in it. This tool is called a diffraction grating. The diffraction grating separates the wavelengths of the light being viewed through it. Hold this slide by the plastic frame; do not touch the clear plastic in the frame.

3. Before making observations, watch your teacher demonstrate for you how to observe the light sources.

4. What do you think you will see when you look at the …
   - white LED directly through the diffraction grating?
   - red LED directly through the diffraction grating?
   - laser light reflected off a sheet of paper through the diffraction grating?

5. Hold the diffraction grating near your eye and look at the lights in your classroom. Describe what you observe. Draw and label a diagram of what you see.

6. As your teacher demonstrated, hold the white LED at about arm's-length and point it sideways, as shown in the drawing. Hold the diffraction grating near your eye and look at the white LED. Draw a diagram showing what you observe, and label the colors that you see.

7. Repeat *Step 6* for the red LED.

Image credit: Nancy Bennett-Karasik @ American Physical Society

Viewing the LED through a diffraction grating

In the next step, for safety, point the laser down at the table, so the beam hits a piece of paper. **Never** look directly into laser light. It can burn your eye.

8. Place a piece of paper on the table, below eye level. Shine the laser light down onto the paper, as shown in the drawing below. View the reflected laser light through the diffraction grating at a distance of an arm's length away. Describe what you observe. Draw a diagram showing what you observe and label the colors that you see.

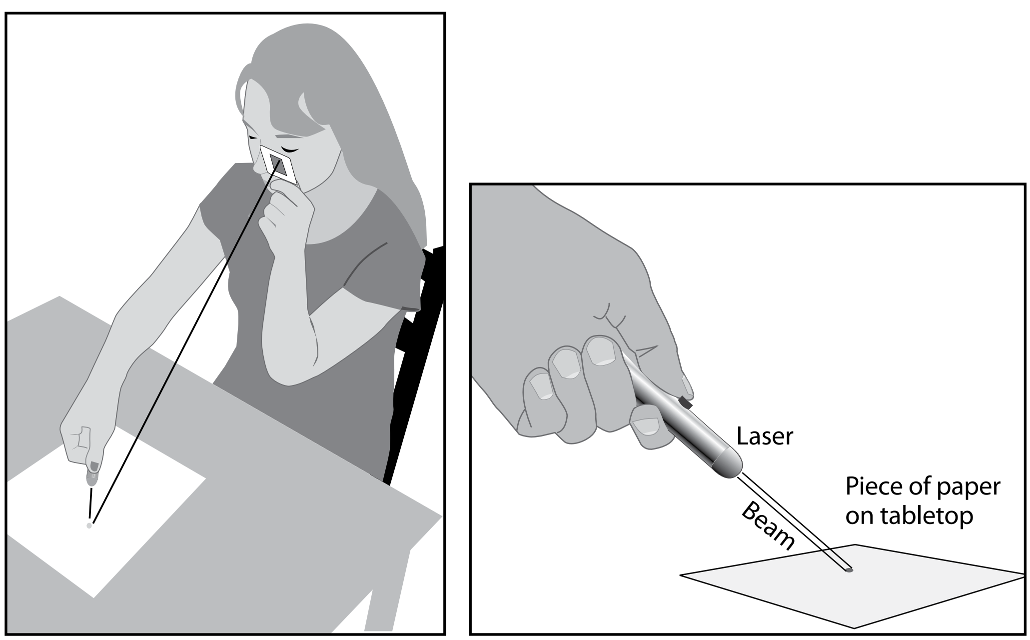


Image credit: Nancy Bennett-Karasik, @ American Physical Society

Viewing the reflected laser light through a diffraction grating

9. Compare your observations of the three light sources.

10. How were your observations the same and different from what you expected to observe?

11. For each light source answer the following questions:

    - Do you think the light source produces a single wavelength or multiple wavelengths?
    - What evidence do you have?

12. Scientists call laser light monochromatic. What do you think this means?

13. **Wrap-up:** What is special about the color of laser light? With your group, come up with your best group answer to this question and support your answer with evidence you obtained from your observations.

B. What's special about how laser light travels?

Materials list
- 1 red LED per group
- 1 laser pointer per group
- 1 meter stick per group
- 1 metric ruler per group
- 1 sheet of white paper (8.5″ x 11″)
- several books

1. With your group discuss what you think is special about laser beams. Do you think a laser beam changes as it travels? Does it spread out like a flashlight beam, or does it do something else? Be ready to share your group's ideas with the class. The goal is to be able to answer this question by the end of *Part B* with supporting evidence.

2. Place a piece of paper on the table. Shine the red LED and the laser pointer down at the paper, keeping the distance between the light sources and the paper the same. Slowly move both light sources a little further away from the paper. Describe what happens to the illuminated area on the paper produced by each light source as the distance between the light source and the paper increases.

3. To gather some quantitative evidence for the laser, you will take three measurements of the illuminated spot's diameter for three different distances between *0* and *100 cm*. First you need to set up the experiment. Place the laser pointer on a book or two to keep it steady. No more than a meter away, tape a piece of paper to a wall or a book. Shine the laser directly at the paper so the beam does not reflect from the book or from the tabletop.

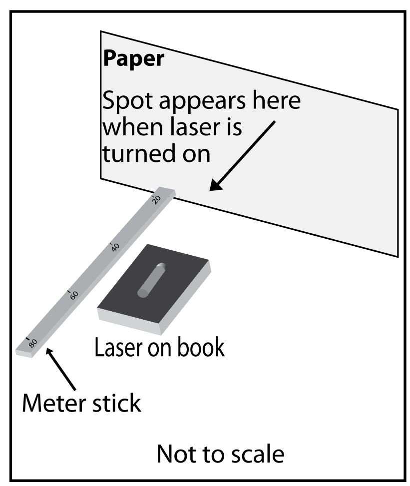


Image credit: Nancy Bennett-Karasik, @ American Physical Society

4. Safety check - Make sure you never look directly into the laser light coming from the laser. When you are doing this experiment, make sure your eye level is above the level of the laser beam. How would you tell this to another student?

5. Measure the distance between the front of the laser and the paper. Outline the illuminated spot on the paper and label this spot with the distance between the laser and the paper. Repeat this for two different distances between the laser and the paper.

6. Measure the diameter of each spot on the paper and record your data in a table like the one below. List the possible sources of error for your experiment.

Distance between laser pointer and paper (cm)	Diameter of illuminated spot on paper (mm)

7. What can you conclude about the laser beam based on your results?

8. Scientists call laser light "collimated." What do you think this means? Share your ideas with your group and be prepared for a class discussion.

9. **Wrap-up:** What's special about how laser light travels? With your group, come up with your best group answer to this question and support your answer with evidence you obtained from your observations.

C. Is there anything else special about laser light?

Materials list
- 1 red LED per group
- 1 laser pointer per group
- 2 copies of sine waves (original is in Teacher Edition) per group
- 1 sheet of white paper (8.5" x 11")

SAFETY REMINDER: Never look directly into a laser beam. Never point the laser towards anyone's eye or toward a highly reflective surface.

1. Hold the laser very close to a sheet of paper so that it makes a small angle with the paper, as shown in the diagram. Turn on the laser.
   - Draw a diagram and describe what you see.
   - What do you think causes this?

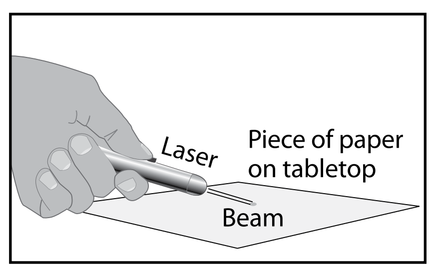


Image credit: Nancy Bennett-Karasik, @ American Physical Society

2. Hold the red LED very close to a sheet of paper, so that it makes a small angle with the paper. Turn on the red LED.
    - Draw a diagram and describe what you see.
    - Compare it to your observations of the laser.

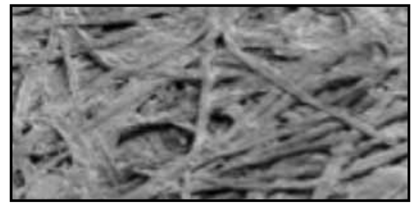


Image credit: Dr. Del Atkinson

Paper Fibers

3. Look at the image of paper fibers and notice how rough the surface of the paper is. When the laser light strikes the paper and reflects off of the paper fibers, the light waves travel various distances to get to your eye. These waves interfere with each other inside your eye to produce the speckled pattern you see.
4. Laser light creates a speckle pattern because the light waves leaving the laser have one wavelength and are in-step. After reflecting from the paper and entering the eye, these waves can either reinforce, producing bright spots, or cancel, producing dark spots.
    - Using two pieces of paper with sine waves on them, show how the reflected laser light creates a dark spot and a bright spot.
    - When the red LED light reflected off of the paper, you did not see a speckle pattern. Why not?
5. Scientists say that laser light is coherent. What do you think coherent means? Have a class discussion on coherent light.
6. **Wrap-up:** What have you learned in *Part C* about how laser light is special? Be prepared to share your group's ideas with the class.

Completing the Lesson: What's special about laser light?

1. What are the properties that make laser light so special?
2. If you have observed or participated in a model in which students represented photons of different light sources, tell what you have learned from this model about different light sources.

Lesson 2. How Does a LASER Work?

Introductory Questions

- What causes laser light to have the special properties you found in *Lesson 1* (monochromatic, collimated, and coherent)?
- What are the essential parts of a laser?

Discuss your ideas with your group and write down your groups' ideas. Be prepared to share your groups' ideas with the class.

Goal

To describe how a laser works.

A. How could you use a computer model to find out how a laser works?

1. You observed a model in which students represented photons and atoms. Describe what you have learned from this model about how atoms and light interact.

2. How do you think you can use a computer model to find out how a laser works?

3. In this part of the lesson you are going to explore a computer model of a laser – but at first, the laser will have only one atom. Open the PhET simulator. Make sure the "one atom" tab is selected, and that the energy levels are set at "two." This will allow you to get an idea of how the simulator works by considering only two energy levels of an atom.

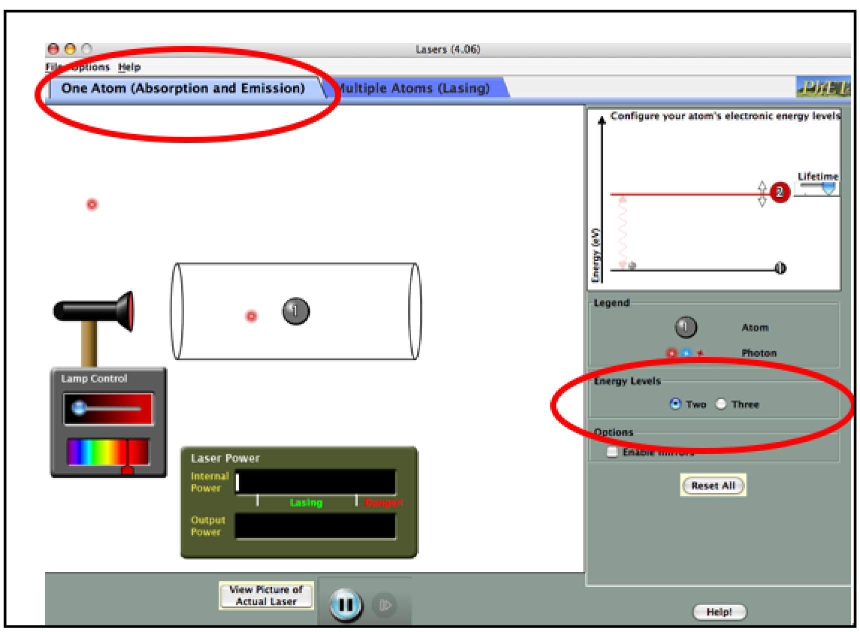


Image credit: PhET Interactive Simulations, University of Colorado
http://phet.colorado.edu

4. Change the settings of the lamp control to observe how this affects the incoming light. See if you can produce all the colors of the rainbow.

    - How can you make the lamp output a lot of photons and just a few?
    - What is this incoming light used for in the PhET simulator?

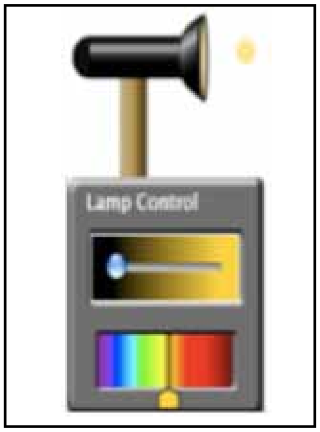


Image credit: PhET Interactive Simulations
University of Colorado
http://phet.colorado.edu

5. Change the settings of the excited level of the atom. See if you can get it to absorb and emit each the colors of the rainbow (red, orange, yellow, green, blue, and violet) – of course not all at the same time!

6. The atom's energy levels are important in determining the input and output energies of the laser. How does changing these allowed energy levels affect the laser?

7. Change the lifetime of the energy level by moving the slider next to the excited state of the atom at the top right of the screen. Describe what affect this has.

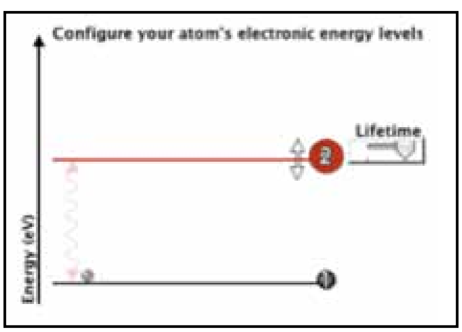


Image credit: PhET Interactive Simulations
University of Colorado
http://phet.colorado.edu

8. Make the energy spacing of the two-level atom correspond to red light. Set the lamp to red light that has just the right energy for the two-level atom. Increase the lamp output so it is maximized. Change the lifetime of the atom. How does changing the lifetime of the atom's energy level affect the system?

9. Keep the settings the same as in *Step 8*, but now turn on the mirrors. The right mirror can be made to be partially reflective. For now keep it at *100%*. When you turn on the mirrors, it turns off the lamp because no light would be able to go through the left mirror. What do you observe?

10. Change the settings to those shown in the image below. Make sure you select the tab on the top for the three-level atom. Note also that there are now two lamps – one for each energy level. One lamp points along the axis of the laser cavity and the other lamp (on top) is perpendicular to the laser axis. Set the lamp above the laser cavity to the energy difference between levels 1 and 3. Set the side lamp to the energy difference between levels 2 and 1. Don't have the mirrors on yet! Watch what happens for at least *30 seconds*. Write down your observations.

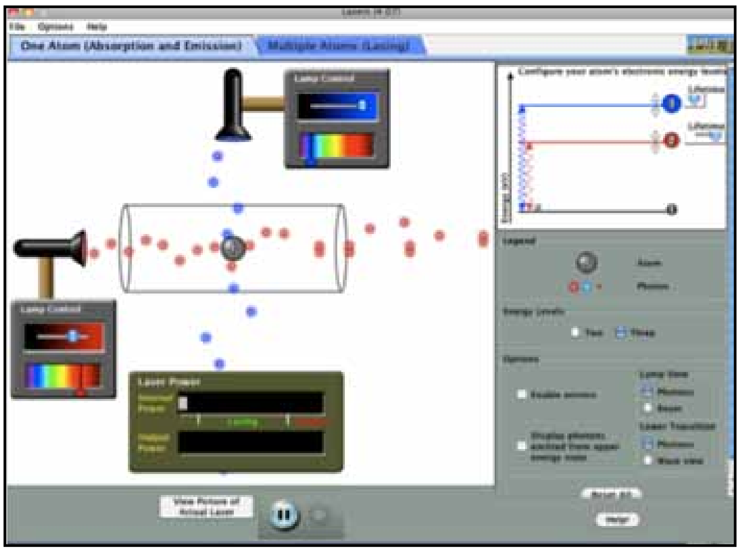


Image credit: PhET Interactive Simulations
University of Colorado
http://phet.colorado.edu

11. Put in the mirrors. The left mirror does not allow any light to go through it (it is *100%* reflective); the right mirror you can adjust. To be a useful laser you want to allow some light to get out. Set the right mirror to *95%*. By putting in the mirrors you turn off the red lamp on the side. Watch what happens for about a minute and describe what you observe.

12. What do you think the advantage is to having three-level atoms? Hint: In this case there is a three-step process
    - The atom is excited into its highest energy level.
    - The atom spontaneously decays to a lower (intermediate) energy level.
    - The atom undergoes stimulated emission from its intermediate energy level to its lowest energy level.

13. With your group, summarize how the PhET simulator helps you to understand how a laser works.

14. **Wrap-up:** Describe how the essential components of a laser produce laser light (light of a single wavelength that is collimated and coherent).

B. What conditions do you need to get the Phet simulator laser to work?

You are going to try to get the PhET simulator to lase (produce laser light). You will need more than one atom, so use the PhET simulator with the multi-atom tab selected.

1. With your group decide on your procedure to make this computer model of a laser work (lase). List all of the variables. For each one determine an initial setting, and why you chose it.

2. As you go through your procedure, record your observations. How do the variables you change affect the lasing process? Record any changes you make and why you made them.

3. What could you do to get the PhET simulator into the danger zone? (See the laser power indicator). Watch out, the laser could blow up!

4. What conditions do you need to get a laser to work? Using what you have learned from the PhET simulator, describe how you could make a working laser.

Lesson 3. What are Some Applications of LASERs?

Introductory Questions

- Where have you seen lasers used?
- Why is it important to learn about lasers?

Share your answers with your group and make a list of your group's ideas. Be ready to share your group's ideas with your class.

Goal: To be able to describe some laser applications.

Safety Reminder: Never look directly into the laser beam. Never look at laser light reflected off of a highly reflective surface like a mirror or a ring. Laser light can cause permanent damage to the eye.

A. How can light transmit sound? [1] (Optional)

Materials list

- Assembled Spectra Sound Kit with speaker
- comb
- laser pointer
- white LED

Discuss with your group how light can be used to communicate. Record your group's ideas. Be ready to share your ideas with the class.

1. Lasers are used to transmit digital data through fiber optic systems. In this investigation you will explore how light can carry information through air. Gather the equipment you will need from your teacher. Note that the photocell has very fragile connections. Handle it carefully and do not touch it directly to make sure that no oils from your hands get on it.

2. Tape the wire leading to the photodetector to a wall below eye level. Do not put any wire near the photocell as it is very fragile. Shine the white LED at the solar cell and turn it on and off. What do you observe?

3. Shine the laser beam on and off of the solar cell. Record your observations.

4. Shine the laser beam on the solar cell and run a comb quickly and slowly through the beam. Record your observations.

5. Plug the headphone jack into a music player and play your favorite song. Point the laser beam at the solar cell. You may have to adjust the volume (turn all the volumes to maximum). Record your observations.

6. In *Step 5*, the signal from the music modulated the amplitude of the laser light, which correspondingly modulated the voltage produced by the solar cell to the speaker.

[1] Adapted from the American Physical Society's Spectra Sound kit

7. Repeat *Step 5* but this time run a comb through the laser beam as it shines on the solar cell. Record your observations.

8. What problems might occur with transmitting information using laser light through air?

B. How thick is your hair?

Materials list
- laser pointer
- empty slide holder
- tape
- meter stick
- metric ruler
- white paper

Criminalists analyze evidence, such as hair and fibers, collected at the scene of a crime. If you didn't have a microscope, how could you use a laser to measure the width of a hair? Discuss your ideas with your group and record your group's best ideas. Be prepared to share your group's ideas with the class.

1. When waves have to go around objects or through small openings, they diffract (spread out). The diffracted waves can interfere, causing what is known as a diffraction pattern.

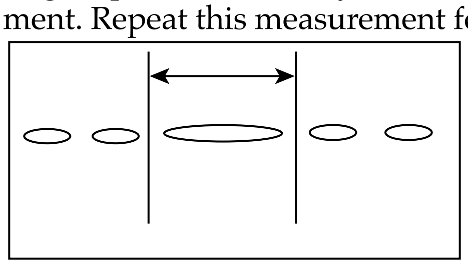
2. What do you think happens when you shine a laser beam at a strand of hair? Collect a strand of hair from several group members. Tape the strands of hair to the slide holder.

SAFETY REMINDER: Never look into the laser beam. Never point the laser at anyone's eye. Never shine the laser on a highly reflective surface, as it may reflect into someone's eye. Lasers can burn the eye causing permanent damage.

3. Set up a white screen, below eye level, in a cardboard box or against a stack of books. Place the slide with the strand(s) of hair one or two meters from the screen and then shine the laser pointer at a strand of hair. Keep the laser steady by having it rest on a desktop. Raise the laser if needed by placing it on a book.

4. Observe the pattern that you see on the screen.
   - Is it a shadow of the hair? Explain your answer.
   - Describe the pattern and make a drawing of it.

5. You should have observed a diffraction pattern similar to the one below. To measure the width of your hair, you will need to measure the distance between the first set of dark spaces in the diffraction pattern. First identify the bright central spot (see central oval in drawing below). Find the middle of the dark spaces between the central spot and the bright spots immediately to the left and the right (see diagram). Record your measurement. Repeat this measurement for each group member's hair.



6. You can calculate the width of the hair using the following mathematical relationship:

$$\text{width of hair} \approx \frac{\text{(wavelength of laser light) (distance from hair to screen)}}{\text{(distance between centers of first dark bands/2)}}$$

7. To measure the distance needed in the denominator in the equation above, simply take your result from *Step 5* and divide it by two.

8. You will need to know the wavelength of the laser light you are using. A range of values might be found on the side of the laser pointer. Calculate the average wavelength and record your calculations. If no values are listed on the laser pointer, assume the following average wavelength: *650nm*.

9. Apply the formula in *Step 7* above to determine the width of the hair. Remember to check your units.

10. Repeat *Step 10* for each hair sample. Record your results.

11. Make a table of your results. Is there a relationship between the width of the hair and the width of the diffraction pattern? Record this relationship.

12. Look at your metric ruler and note the distance of *1 mm* (*0.001 m*). How many strands of your hair could you fit in *1 mm*?

13. How else could this technique of measuring small distances with a laser be used?

C. How could you model X-ray diffraction of DNA?

Materials list
- laser pointer
- spring
- tape
- meter stick
- white paper

Just as you used the diffraction of laser light to measure the width of a hair, scientists used X-ray diffraction to measure the structure of molecules. Discuss with your group how diffraction of laser light could be used to model X-ray diffraction. Record your best group answer and be ready to discuss your ideas with the class.

1. Discuss what you know about DNA with your group. Record your groups' ideas. Be ready to share your ideas with the class.

2. This image shows Rosalind Franklin's x-ray diffraction pattern of DNA. DNA is the helical molecule that carries genetic information. James Watson (one of the discoverers of DNA) said, "The instant I saw the picture my mouth fell open and my pulse began to race ..." (from his book *The Double Helix*). Before the image shown was observed, scientists did not have conclusive evidence of DNA's shape. A molecules shape is important because it helps determine properties of the molecule and how it will interact with other molecules.

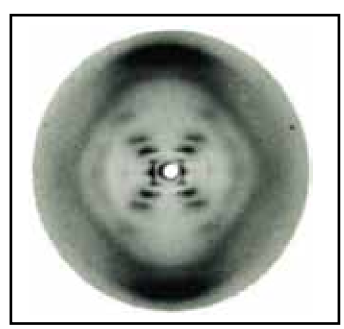


Image credit: Reprinted by permission from Macmillan Publishers Ltd: *Nature* 171, 740-741, © 1953

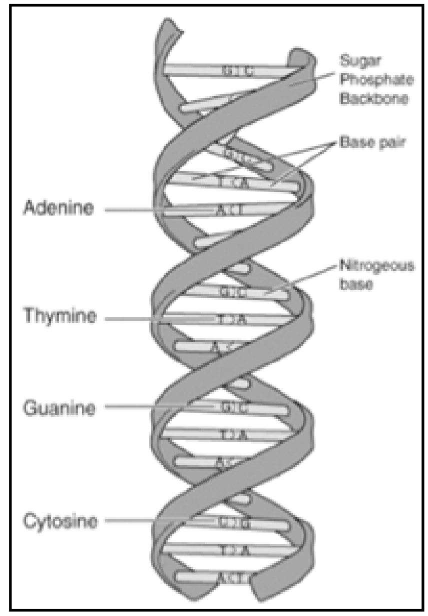
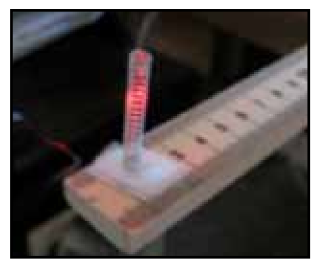


Image credit: Wikimedia Commons

Watson used the information in the image on the right to verify the correctness of the model of DNA that he and Francis Crick developed in the early 1950s. Their work won them the Nobel Prize. (To find out more visit the Exploratorium's website, which has an annotated version of the Crick & Watson's paper announcing their discovery of DNA in the scientific journal *Nature*).

3. A helix is like a three-dimensional spiral. A spring of a retractable ballpoint pen is an everyday example of a helix. In this part of the lesson you will make a model to simulate an X-ray diffraction pattern of a DNA molecule, using a laser and a spring.

   Set up a piece of white paper (preferably in a cardboard box or on a stack of books) – below eye level. Place a meter stick along the table or floor with the paper at one end. At the other end of the meter stick, place a small piece of double-sided tape or a loop of tape. Place a spring on top of the tape as shown in the image below. Don't shine the laser light yet!



4. Place the laser near the spring on a stack of books to raise and to stabilize the laser. Shine the laser at the spring, keeping your eyes above the laser light level. You should see a diffraction pattern on the screen. As you observe the diffraction pattern, make sure that the laser level is well below eye level. Record your observations by drawing a diagram of what you see and describing it.

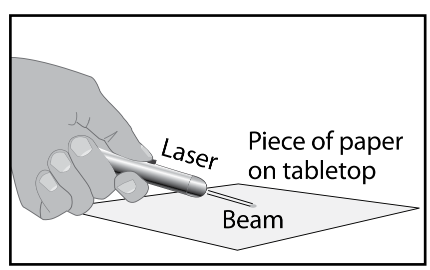
5. How is shining laser light at a spring similar to making an X-ray diffraction of DNA? With your group answer the question. Record your answer.

6. If you couldn't see or touch the spring, what could you learn about the spring from the diffraction pattern?

D. What can speckle patterns be used for?

Materials list
- laser pointer
- white paper

Discuss with your group what you know about speckle patterns (e.g. what causes them?) and what you think they could be used for. Record your group's ideas. Be ready to share your ideas with the class.



1. Place a piece of paper on your table. Hold the laser so the beam makes a very small angle with the paper surface, as shown in the drawing. Describe what you see.

2. Create the laser speckle pattern on a sheet of paper again, and slowly move your head back and forth. Make sure each group member gets to make observations. Describe what you observe.

3. Now produce the speckle pattern again, and move the paper from side to side. As you do this, keep your head and the laser as still as possible. Describe what you observe.

4. Shine the laser at a small angle in the crook of your inner elbow. Keep your head still. What do you see? Record your observations and your group members' observations. Compare your observations of the speckle pattern on your skin with the speckle pattern observed when you moved the paper. Have a group discussion on your results. What do you think causes this?

   Cool Fact: Tiny changes in the surface of your skin from muscle movements and movement of blood near the surface of the skin cause the rapid changes in the speckle pattern you observe on your skin. The speckle pattern changes very rapidly – on the order of milliseconds. Do you think your eyes could keep track of changes that occur every thousandth of a second?

5. By tracking how the speckle pattern changes in time scientists can determine the speed of the blood flow! A system developed using laser speckle imaging employs a high-resolution camera and a computer to analyze how the speckle pattern changes on the scale of milliseconds. This information could help surgeons determine how well blood flows in the tissue of a skin graft.

   In the laser speckle imaging picture shown (which is not a photograph), one can clearly see the difference in blood flow between the body temperature finger on the left and the finger that was warmed in hot water on the right. When your body temperature increases, the blood flow increases.

   Summarize how laser speckle is used in this situation. Discuss this with your group members.

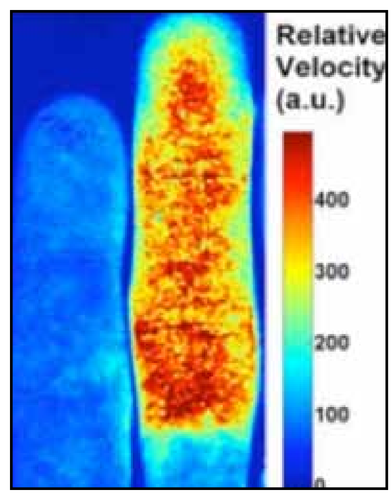


Image credit: Michael Smith, Institute for Biodiagnostics, Winnipeg, Canada.

Laser speckle imaging of blood flow in warmed finger on right and body temperature finger on left, in arbitrary units of velocity.

Please note that this is not a photograph of the speckle pattern.

6. What can speckle patterns be used for? Answer the question with your group and list your ideas about what speckle patterns could be used for. Be ready to share your ideas with your class.

EXTRA! EXTRA! READ ALL ABOUT IT!

Using lasers to create a star in the lab!

One of the newest lasers is at the National Ignition Facility in Livermore, California. This laser produces beams carrying 60 times more energy than other lasers. It is be used to ignite a nuclear-fusion reaction. With two million Joules of energy focused on a pea-sized capsule of hydrogen isotopes inside a chamber, a star will be born inside the laboratory! This laser will provide insights into stars, and may lead to improvements and insights into controlling the fusion reaction to produce electrical energy. This would make it a useful alternative energy source to burning coal.

To learn more conduct an Internet search on the following key words, "National Ignition Facility, world's largest and highest energy laser".

The American Physical Society
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College Park, MD 20740-3844

www.aps.org
www.laserfest.org