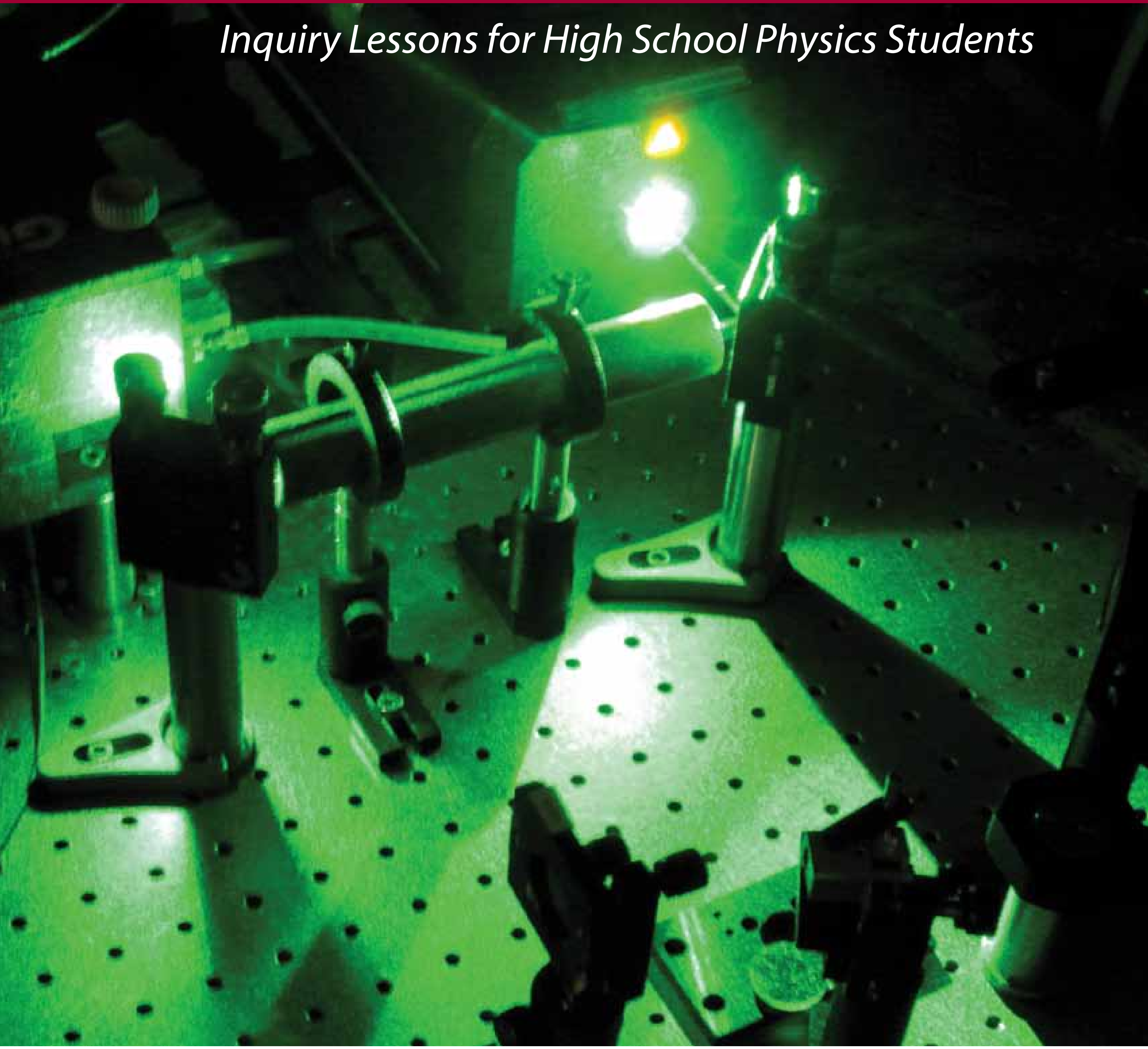
Teacher Edition

The Physics of LASERs



Inquiry Lessons for High School Physics Students

Heide Doss, Ed Lee, and Monica Plisch

LASER FEST CELEBRATING 50 YEARS OF LASER INNOVATION
APS physics
NATIONAL SCIENCE FOUNDATION
U.S. DEPARTMENT OF ENERGY

Acknowledgments

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Lesson 2 of *The Physics of LASERs* is based on the PhET Lasers simulation, which was produced in the physics department of the University of Colorado at Boulder. We highly recommend the PhET simulations to physics students and teachers.

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*

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Introduction to Teacher Edition

Summary for all Lessons

These lessons were written to celebrate the 50th birthday of the LASER. The first working LASER was created on May 17, 1960.

This set of three laser lessons introduces students to the properties of lasers, the fundamental components of a laser, and some applications of lasers. The first lesson provides students with hands-on experiences to gain understanding of the special properties of laser light: monochromatic, collimated, and coherent. The second lesson focuses on the parts of a laser (an energy source, an active medium, and a resonant cavity), and has students explore how to build a laser using a computer simulation (PhET simulator from the University of Colorado at Boulder). In the third lesson students investigate applications of the laser. Students explore how information is transmitted using light, use lasers to measure the width of a hair, model X-ray diffraction of DNA, and produce a speckle pattern like that used to measure blood flow. By the end of these lessons students should have a good idea of what makes laser light special, how it is produced, and how it can be used.

You can find more information about lasers at the LaserFest and PhysicsCentral websites.

Using this Teacher Edition

Written instructions within the teacher's edition are meant for the teacher to use to assist students. In general the student's edition is not to be used as a set of instructions that students independently follow. The only parts of the lesson that students could do independently are in *Lesson II, Parts A* and *B* that have students explore how to build a laser using a computer simulation.

To reduce photocopying, a single class set of student lesson sheets could be produced and used for all classes. Students could record their responses on their own paper.

The following symbols appear within these lessons:

(record results) (discuss) (safety)

Prerequisites

These lessons assume that students understand the following concepts:

- Light travels in straight lines.
- Light is an electromagnetic wave.
- Light can be represented as a particle (photon - a packet of light energy).
- Waves can interfere.
- Different colors of light have different wavelengths.

Safety

Lasers are powerful light sources that can harm the eye, and even though some are inexpensive, they are not toys. If a student stares deliberately into a laser beam, permanent and irreparable eye damage can occur. Because of this, it is suggested that students use a Class II laser. Class II lasers are no more powerful than *1 mW* and the blink reflex will prevent eye damage, unless deliberate staring into the beam occurs. Most laser pointers are Class III A lasers, which are rated up to *5 mW*. Class III A lasers can cause permanent and irreparable eye damage if they are used with lenses and mirrors or if direct viewing of the beam occurs. Viewing of the beam reflected from surfaces such as mirrors will also cause permanent and irreparable damage. To reduce the chance of eye damage, do not completely darken the room.

This unit specifies several simple precautions that prevent direct viewing of the beam:

- Students perform the activities in a normal sitting position, so their eyes are well above the level of the tabletop.
- The laser is placed at or very near tabletop level, and is aimed either horizontally or down at the table.

The National Science Teachers Association recommends that students below high school level should not handle laser pointers, rather the teacher should perform demonstrations with the laser pointer.[1] Additionally, it is suggested that safety posters be displayed in the classroom when using lasers. If conducting the optional *Part A* of *Lesson 3*, review the safety issues involved with the different classes of lasers. The Spectra Sound kit includes in it a Class III A laser. Safety information for lasers can be found online by conducting an Internet search on "laser safety".

[1]Roy, K. (2007). *Shedding Light on Laser Pointer Safety*, Science Scope, Summer 2007

Materials

Complete Kit List

Item	Used in Lesson
1 red LED per group	1
1 white LED per group	1, 3
1 laser pointer (class II) per group	1, 3
1 diffraction grating per group	1
1 spring per group	3
1 slide holder per group	3
Optional – Spectra Sound kit[1](http://www.laserfest.org/about/store/)	3

Additional Materials Needed

Item	Used in Lesson
projection system	1, 2, 3
meter stick	1, 3
1 flashlight – teacher demonstration	1
masking tape	1, 2, 3
colored markers	1, 2
colored paper such as sticky notes (red, orange, yellow, blue, green, and purple)	1
construction paper (red)	2
optional box or box lid to block ambient light	1, 3
optional: 1 bulb in bulb holder, 2 batteries, 3 connecting wires, and aperture per group	1
computer(s) per group or class with PhET simulator downloaded or internet connection, found at URL listed below or by conducting an Internet search on the words, "PhET laser simulator" http://phet.colorado.edu/simulations/sims.php?sim=Lasers	2

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

Timeline for Lessons

The full set of *Laser Lessons* takes approximately 200 minutes or five 40 minute class periods. *Lesson 1* takes approximately 80 minutes (two 40 minute class periods). *Lesson 2* takes approximately 80 minutes or 40 minutes if *Parts A* and *B* are assigned as out-of-class work. *Lesson 3* takes one 40 minute class.

If you have limited time; after completing *Lesson 1*, consider doing only the explanation part of *Lesson 2* during class time. *Lesson 2*, *Parts A* and *B* can be assigned as homework or skipped if needed. We recommend completing *Lesson 3*.

National Education Standards Addressed by Laser Lessons

These lessons may address some of your state science standards. Some common national standards for 9th-12th grade that this lesson addresses or meets are listed on the following pages.

American Association for the Advancement of Science (AAAS) Benchmark	Lessons
Nature of Science	
Investigations are conducted for different reasons, including: to explore new phenomena, to check on previous results, to test how well a theory predicts, and to compare theories. 1B/H1	1, 2, 3
There are different traditions in science about what is investigated and how, but they all share a commitment to the use of logical arguments based on empirical evidence. 1B/H4*	1, 2, 3
To be useful, a hypothesis should suggest what evidence would support it and what evidence would refute it. A hypothesis that cannot, in principle, be put to the test of evidence may be interesting, but it may not be scientifically useful. 1B/H9** (SFAA)	1
Bias attributable to the investigator, the sample, the method, or the instrument may not be completely avoidable in every instance, but scientists want to know the possible sources of bias and how bias is likely to influence evidence. 1B/H10** (SFAA)	1, 3
Because science is a human activity, what is valued in society influences what is valued in science. 1C/H10** (SFAA)	3
The Nature of Technology	
One way science affects society is by stimulating and satisfying people's curiosity and enlarging or challenging their views of what the world is like. 3A/H3b*	1, 3
The Physical Setting	
Waves can superpose on one another, bend around corners, reflect off surfaces, ... these effects vary with wavelength. 4F/H6ab	1, 2, 3
The energy of waves (like any form of energy) can be changed into other forms of energy. 4F/H6c	2
Although the various forms of energy appear very different, each can be measured in a way that makes it possible to keep track of how much of one form is converted into another. Whenever the amount of energy in one place diminishes, the amount in other places or forms increases by the same amount. 4E/H1*	2
When energy of an isolated atom or molecule changes, it does so in a definite jump from one value to another, with no possible values in between. The change in energy occurs when light is absorbed or emitted, so the light also has distinct energy values. The light emitted or absorbed by separate atoms or molecules (as in a gas) can be used to identify what the substance is. 4E/H5*	2
If no energy is transferred into or out of a system, the total energy of all the different forms in the system will not change, no matter what gradual or violent changes actually occur within the system. 4E/H10** (SFAA)	2
*In empty space, all electromagnetic waves move at the same speed—the "speed of light." 4F/H3c**	*1 (could be discussed)*
The Designed World	
Lasers are a new tool for focusing radiation energy with great intensity and control. 8C/H1c	1, 2, 3
… The instructions and data input of a computer model try to represent the real world so the computer can show what would actually happen. In this way, computers assist people in making decisions by simulating the consequences of different possible decisions. 8E/H1	2
Common Themes	
Understanding how things work and designing solutions to problems of almost any kind can be facilitated by systems analysis. In defining a system, it is important to specify its boundaries and subsystems, indicate its relation to other systems, and identify what its input and output are expected to be. 11A/H2	2

Models are often used to think about processes that happen too slowly, too quickly, or on too small a scale to observe directly. They are also used for processes that are too vast, too complex, or too dangerous to study. 11B/M1*	1, 2, 3
Computers have greatly improved the power and use of mathematical models by performing computations that are very long, very complicated, or repetitive. Therefore, computers can reveal the consequences of applying complex rules or of changing the rules. The graphic capabilities of computers make them useful in the design and simulated testing of devices and structures and in the simulation of complicated processes. 11B/H2*	2, 3
Whatever happens within a system, such as parts exploding, decaying, or reorganizing, some features, such as the total amount of matter and energy, remain precisely the same. 11C/H10** (SFAA)	2
Graphs and equations are useful (and often equivalent) ways for depicting and analyzing patterns of change. 11C/H4	3
Representing very large or very small numbers in terms of powers of ten makes it easier to perform calculations using those numbers. 11D/H1*	3
Habits of Mind	
Exhibit traits such as curiosity, honesty, openness, and skepticism when making investigations, and value those traits in others. 12A/H1*	1, 2, 3
View science and technology thoughtfully, being neither categorically antagonistic nor uncritically positive. 12A/H2	1, 2, 3
Scientists value evidence that can be verified, hypotheses that can be tested, and theories that can be used to make predictions. 12A/H4** (SFAA)	1, 2, 3
Curiosity motivates scientists to ask questions about the world around them and seek answers to those questions. Being open to new ideas motivates scientists to consider ideas that they had not previously considered. Skepticism motivates scientists to question and test their own ideas and those that others propose. 12A/H5*	1, 2, 3
Find answers to real-world problems by substituting numerical values in simple algebraic formulas and check the answer by reviewing the steps of the calculation and by judging whether the answer is reasonable. 12B/H2*	3
When describing and comparing very small and very large quantities, express them using powers-of-ten notation. 12B/H6*	3
Consider the possible effects of measurement errors on calculations. 12B/H9	1, 3
Follow instructions in manuals or seek help from an experienced user to learn how to operate new mechanical or electrical devices. 12C/H1*	3 (optional part)
Make and interpret scale drawings. 12D/H1	1, 2, 3
Use and correctly interpret relational terms such as *if… then…*, *and*, *or*, *sufficient*, *necessary*, *some*, *every*, *not*, *correlates with*, and *causes*. 12D/H5	1, 2, 3
Participate in group discussions on scientific topics by restating or summarizing accurately what others have said, asking for clarification or elaboration, and expressing alternative positions. 12D/H6	1, 2, 3
Use tables, charts, and graphs in making arguments and claims in oral, written, and visual presentations. 12D/H7*	1, 2. 3
Use symbolic equations to represent relationships between objects and events. 12D/H8**	3

Notice and criticize claims based on the faulty, incomplete, or misleading use of numbers, such as in instances when (1) average results are reported but not the amount of variation around the average, (2) a percentage or fraction is given but not the total sample size, (3) absolute and proportional quantities are mixed, or (4) results are reported with overstated precision. 12E/H1*	1, 2, 3
Consider whether some event of interest might have occurred just by chance. 12E/H3*	1, 3
Insist that the key assumptions and reasoning in any argument—whether one's own or that of others—be made explicit; analyze the arguments for flawed assumptions, flawed reasoning, or both; and be critical of the claims if any flaws in the argument are found. 12E/H4*	1, 2, 3
Notice and criticize claims that people make when they select only the data that support the claim and ignore any that would contradict it. 12E/H5*	1, 2, 3
Notice and criticize arguments in which data, reasoning, or claims are represented as the only ones worth considering, with no mention of other possibilities. 12E/H6a*	1, 2, 3
Suggest alternative trade-offs in decisions and designs and criticize those in which major trade-offs are not acknowledged. 12E/H6b	1 (Optional activity only), 2

National Science Education Standards (NSES)	**Lessons**
Unifying Concepts and Processes	
Systems, order, and organization	1, 2, 3
Evidence, models, and explanation	1, 2, 3
Change, constancy, and measurement	1, 2, 3
Science as Inquiry	
Abilities necessary to do scientific inquiry	1, 2, 3
Understandings about scientific inquiry	1, 2, 3
Physical Science	
Motions and forces	1, 2, 3
Interactions of energy and matter	1, 2, 3
Structure of atoms	2
Structure and properties of matter	2
Conservation of energy and increase in disorder	2
Science and Technology	
Understandings about science and technology	1, 2, 3
Abilities of technological design	2
Science in Personal and Social Perspectives	
Natural and human-induced hazards	1, 2, 3
Science and technology in local, national, and global challenges	1, 3
History and Nature of Science	
Science as a human endeavor	1, 2, 3
Nature of scientific knowledge	1, 2, 3
Historical perspectives	1 (optional video at end), 3

Lesson 1. What's Special about LASER Light?

Goal

Through an investigation students describe properties that distinguish laser light from other common light sources, namely that it is monochromatic, collimated, and coherent.

Time: 80 minutes

Summary of Lesson 1

In the first part of this lesson students obtain evidence to support the idea that laser light is monochromatic (of a single color, or equivalently, a single wavelength). They observe how light from a red laser pointer, a red LED, and a white LED interact with a diffraction grating. Their observations provide evidence that the light from the red and white LEDs is composed of more than one color (more than one wavelength), whereas the laser light contains only one color (only one wavelength).

During the second part of this activity, students are provided with evidence that laser light is collimated (the light produced is composed of parallel light waves). By comparing how laser light and red LED light spread as they travel, students obtain qualitative evidence. Students then collect quantitative evidence by measuring how the beam width varies with distance. As an enrichment activity students could quantitatively compare the collimation of laser light and another light source (e.g. a bulb).

The third part of this activity presents students with the concept of coherence. Coherent light is composed of light waves that have a constant relative phase. Students shine LED and laser light on paper and compare the reflections. With a discussion about the interference of light waves reflected off the paper and entering the eye, students explain their observations. After these experiences, students are introduced to the concept of coherence.

Students participate in a kinesthetic model in which the students model the light from a white LED, a red LED, and a laser. The class concludes this lesson by summarizing the special properties of laser light.

Prerequisites

These lessons assume that students understand the following concepts:

- Light travels in straight lines.
- Light is an electromagnetic wave.
- Light can be represented as a particle (photon - a packet of light energy).
- Waves can interfere.
- Different colors of light have different wavelengths.

Materials

- 1 red LED per group
- 1 white LED per group
- 1 laser pointer per group
- 1 meter stick per group
- 1 sheet of white paper per group
- 1 diffraction grating per group
- optional: 1 box or box lid per group, to help block ambient light
- masking tape
- colored paper or cards in red, orange, yellow, green, blue, and violet
- optional: Colored markers (red, orange, yellow, green, blue, violet)
- optional: Masking tape marked with the six colors listed above or colored tape
- optional: 1 bulb in bulb holder, 2 batteries, 3 connecting wires, and aperture per group
- optional: rigid object, like a meter stick, to help students understand that light of different colors travels at the same speed

⚠ Safety

Lasers are powerful light sources that can cause permanent eye damage. If a student stares deliberately into a laser beam, permanent and irreparable eye damage can occur. Because of this, it is suggested that students use a Class II laser. Class II lasers are no greater than *1 mW*, and the blink reflex will prevent eye damage, unless deliberate staring into the beam occurs. Most laser pointers are Class III A lasers, which are up to *5 mW*. Class III A lasers can cause permanent and irreparable eye damage if they are used with lenses or mirrors or if direct viewing of the beam occurs. Direct viewing of the beam off of highly reflective surfaces such as mirrors can also cause permanent and irreparable damage. The National Science Teachers Association recommends that students below high school level should not handle laser pointers, rather the teacher should perform demonstrations with the laser pointer.[1] Additionally, it is suggested that safety posters be displayed in the classroom when using lasers.

To reduce the chance of eye damage, do not completely darken the room.

[1]Roy, K. (2007). *Shedding Light on Laser Pointer Safety*, Science Scope, Summer 2007

Lesson 1 - Teacher Edition

Preparation before class

Cut the plastic grating sheet to fit the slide mount. It should be slightly larger than the slide opening and should not overlap any of the pins. Tape the slide together on all four sides so the grating cannot drop out. You will need one mounted diffraction grating per group.

In the last part of *Lesson 1*, students will take part in kinesthetic models to help them understand the properties of laser light. Students will model the different light sources they observed by representing photons (packets of light energy) that the light sources produce. Their stride length will represent the wavelength (color). Red light will have the longest wavelength and hence the red stride length should be the longest (about 1 m). Violet light will have the shortest wavelength, and has just over half the wavelength of red light, so it should be represented by just over half the stride length selected for red light. In order to simulate the mirrors of a laser cavity, you will need a space about five students wide, and long enough to allow at least five stride lengths representing red light. Use objects such as walls or desks to represent the two mirrors of the laser cavity. If your floor has a pattern on it, you could determine the lengths based on some amount of the pattern, for example, 2.0 tiles for violet light, 2.5 tiles for green light, 3.0 tiles for red light. Another method might be to lay down meter sticks on the floor and label them with colored sticky notes.

A table with the approximate range of wavelengths for each color in the visible spectrum, the average wavelength for each, and a suggested value for the stride length is provided below.

Color of Light	Approximate range of wavelengths (nm)	Suggested Stride length
Red	635-700	1 (set = 1 m)
Orange	590-635	0.92
Yellow	560-590	0.86
Green	490-560	0.79
Blue	450-490	0.70
Violet	400-450	0.64

Note: You could emphasize the relationship between frequency and wavelength by having one student represent a red light wave, and another represent violet, but have the student representing violet light take “baby” steps for its wavelength and the student representing red light take “giant” steps. Since light waves travel at the same speed in air, the two students would have to stay side-by-side as they walked around, showing that they travel at the same speed. This is a good way to emphasize that violet light has a small wavelength (step length) and a high frequency (number of steps per second), whereas red light has a large wavelength (step length) and a low frequency (number of steps per second). You should emphasize that this is an exaggeration of the difference between the wavelengths of visible light so that students do not end up with misconceptions about their wavelengths and frequencies.

Teacher’s Notes

I. What's Special about Laser Light?

Introductory Questions

You could use these questions as a warm up for the class. Consider having them displayed when students walk in the classroom.

Facilitate a class discussion on students' initial ideas about properties of laser light, and encourage students to provide their reasoning. Record students' ideas as you may want to revisit these ideas at the end of this lesson.

Some initial ideas students have expressed about laser light:

Laser light is fast, bright, fluorescent, not fluorescent, infrared, many colors, one color, can be different colors, red, blue, green, not white. You can see the thin line going to a dot of light - like the laser line for building things, or laser lines used to detect if an object is in the way of garage doors. The most common laser light is red because it can travel the farthest. Laser light is special light that can blind people. Lasers can be weapons. Lasers are like a frequency. Most lights like the ones above us are burning out and dispersing, but lasers last longer and they can't bounce off of objects; you see an object because light reflects off of it but a laser is not reflective like that.

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

Notes on Student Edition, Part A, Step 1

It is generally good practice when teaching a concept to have students verbalize what they think first and then do an activity that refutes misconceptions and supports correct ideas. Students should discuss what they think after the activity based on their observations and logical reasoning.

Have a **class discussion** on students' ideas. Having students consider this question will focus their thinking as they do the activity and it will provide you with some of their prior knowledge and possible misconceptions that may be addressed with this activity.

Goal of Part A: Students should be able to state that laser light is monochromatic and provide some supporting evidence for this.

Some initial ideas students have expressed about the color of laser light:

fast, bright, fluorescent, not fluorescent, infrared, many colors, one color, can be different colors, red, blue, green, not white. Some colors can't be made, for example, colors not seen by the human eye. Red is the most common laser light because it can travel the farthest. Red is the most concentrated [bright] light. Most lasers are red because it is easy to see, can see through smoke. Lasers like a frequency, most lights like the ones above us are burning out and dispersing, but lasers last longer and they can't bounce off objects, see white board because light reflects off of it but a laser is not reflective like that. Maybe each color can do different things. Maybe [there are] 3 or 4 colors.

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.

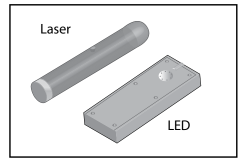
Safety

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")



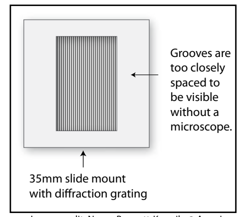


Image credit: Nancy Bennett-Karasik, @ American Physical Society

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.

Student Version Page 2

Part A, Step 3

Demonstrate for students how to hold the LED light sources and view them through the diffraction grating. (See the diagram in the Student Edition, *Step 4*). In one hand, hold the diffraction grating by its frame, near your eye. In the other hand, at an arm's length away, hold the LED so it points sideways (not directly at the eyes). The purpose of this is to make the LED as much of a point source as possible, which will make it easier to notice the diffracted light, and this is generally safer for the eye. **Emphasize to students not to look into the laser beam.** They should shine the laser off of a non-shiny surface that is below eye level. The laser should be held an arms length away, pointing down toward the surface below eye level, and the diffraction grating should be held near the eye.

Point out to students that this isn't a fair test because the light sources are being viewed differently. However they cannot look at the laser beam directly. The reflected laser light off of the table is not as strong and gives similar results when viewing it through the diffraction grating.

Have students read *Steps 4* through *8*. Let students know how much time they have to complete *Steps 4* through *8*, and then darken the room.

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.

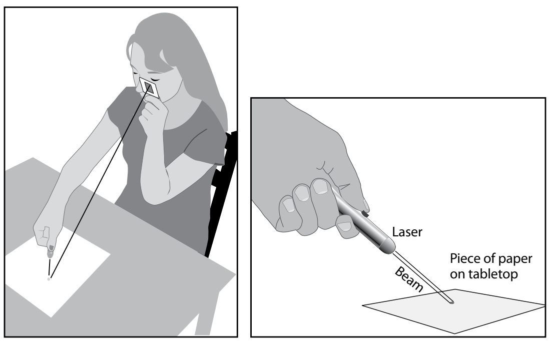


Image credit: Nancy Bennett-Karasik, @ American Physical Society

Viewing the reflected laser light through a diffraction grating

Student Version Page 3

Part A, Step 4

Check that students record their expectations of what they will observe.

Part A, Step 6

Check students' responses. Students' descriptions should be similar to those listed below. Encourage students to list all the colors, the patterns, and shapes in their diagrams.

Troubleshooting: Students should hold the diffraction grating near their eye. Rotating the grating by 90˚ will rotate the diffraction pattern by 90˚. Let students know that there may be diffracted ambient light that affects what they are viewing. Make sure the room lights are dimmed. To help students identify the light from the LED, have them move the LED back and forth and look for light patterns moving in the same way. Reflected light off of the surface of the light source will also move; if they are seeing this, the lights can be dimmed further or a box could be used to shield the ambient light.

White LED viewed through a diffraction grating.

Image credit: Ken Cole, APS

The photograph and photocopying may not show the actual colors observed.

Note the colors observed (red, orange, yellow, green, blue, and violet) and the pattern observed (a narrow strip of light containing the colors of the rainbow).

Part A, Step 7

Check students' responses. Students' descriptions should match those below. Encourage students to list all the colors, the patterns, and shapes in their diagrams. Again, if students are having trouble viewing the source they should follow the procedure described in *Step 6* troubleshooting.

Red light viewed through a diffraction grating.

Image credit: by Ken Cole, APS

The photograph and photocopying may not show the actual colors observed.

The red LED produces red, orange, yellow, and green light. Students may not observe all of these colors. The pattern should be similar to the pattern formed by the white LED.

Part A, Step 8

Check students' responses. Students' descriptions should be similar to the descriptions listed for the red laser pointer. Encourage students to draw detailed diagrams.

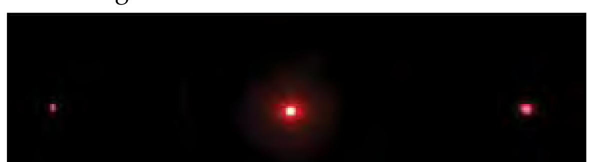


Image credit: by Ken Cole, APS

Reflected red laser pointer shining from a desk top when viewed through a diffraction grating.

Only red light is observed. The pattern is a bright central spot along with two diffracted spots as shown in the photograph above. This narrow diffraction spot suggests that the red laser light is composed of one wavelength of light. (Note: if the diffracted light were a strip, rather than a dot, it would indicate that the red light was composed of a number of wavelengths).

FYI: Laser light actually consists of a tiny range of wavelengths, but this range cannot be observed with the equipment used in this lesson.

Part A, Step 9

Check students' responses. When viewing the LEDs through the diffraction grating, students should note that in the center of their field of view they saw the source almost unchanged from viewing without the diffraction grating. Students should describe a strip of different colors off to each side of the field of view. For the laser, only a small dot is observed in the center and off to each side. The side dots are not spread out and are only one color. If students do not notice the difference between the red LED and the laser, have them repeat *Steps 7* and *8*.

As a class review students' observations and make sure all groups have noticed multiple colors for the white LED, more than one color for the red LED (usually red, orange and yellow are observed, and sometimes green), and just one color for the laser.

As a class complete the rest of *Part A.*

Let the class know that although the slide looks like a piece of clear plastic, it has thousands of very closely spaced parallel grooves. These grooves cause the light to spread out (diffract) according to their wavelength or frequency. Each wavelength (or frequency) of light is associated with a different energy, and each is part of the electromagnetic spectrum.

Note: The diffraction pattern of the white LED provides evidence that white light is made up of many colors. The colors of a rainbow provide further evidence that white light is made up of many colors (although the rainbow colors are caused by refraction rather than diffraction).

Consider discussing living creatures that see in other parts of the spectrum; for example, bees and butterflies can see in the ultraviolet.

Discuss the electromagnetic spectrum with the class. **Describe** how the wavelength changes as the colors in the spectrum go from violet to red. The wavelength increases as the visible spectrum goes from violet to red.

Part A, Step 10

Check that students describe how their observations differed from what they expected to observe. Their expectations were described in *Step 3.*

Part A, Step 11

Briefly **discuss** the observation that the grating separates the components of the light source.

Example response follows. Check for evidence supporting claims.

> Both LEDs produce multiple wavelengths. We think this because when we viewed the light they produce through a diffraction grating we saw a spread of light of different colors. The white LED produced red, orange, yellow, green, blue, and purple. The red LED produced red, orange, and yellow light.
>
> We concluded that laser light is made up of one wavelength, because when we viewed its reflected light through the diffraction grating it produced only one color of light – red. Also, the diffracted light we observed off to the sides was not spread out.

---

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.

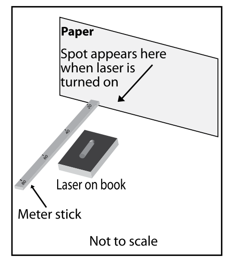


Image credit: Nancy Bennett-Karasik, @ American Physical Society

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.

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Part A, Step 12

Introduce the term monochromatic, which means single wavelength or one color. Have students consider each part of the word: mono means one, chromatic is related to color. In reality laser light is composed of a narrow range of wavelengths.

Part A, Step 13

Have groups answer this question and present their answers to the class. Have the class come to a consensus on how to answer this question along with providing their evidence.

Example answer: "Laser light is made up of only one wavelength of light. The evidence we have to support this is our observations of light through a diffraction grating. Diffraction gratings spread out the light according the light's wavelength. For the white LED we observed that the diffracted light had spread out and contained many colors. For the red LED the diffracted light was spread out and had few colors. For the laser we did not see the diffracted light spread

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?

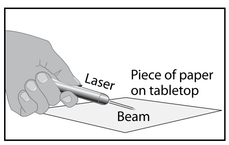

Image credit: Nancy Bennett-Karasik, @ American Physical Society

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and it was just one color. From this we conclude that the laser light is composed of one wavelength. Different colors of light have different wavelengths."

Make sure students understand that each color of light represents a different wavelength of light.

Did students reach the goal of Part A? Students should be able to state that laser light has one wavelength and provide some supporting evidence for this. Note: Careful measurements with special equipment show that laser light is in fact composed of a narrow spread of wavelengths (or equivalently, frequencies). Laser light is almost monochromatic (consisting of a single wavelength/frequency).

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

Note on Student Edition, Part B

Demonstrate laser light traveling through space by shining the laser pointer at a wall in the room.

Notes on Part B, Step 1

Have a class discussion about what students think the answers to these questions are.

Goal of Part B: Students should be able to state that laser light is very collimated (the light produced is composed of light rays traveling parallel to each other) and provide supporting evidence for this. If you do the optional enrichment they should be able to say that laser light is more collimated than light produced by other sources and provide some supporting evidence for this.

Part B, Step 2

Students should see that the illuminated area from the red LED increases a lot as the distance between the red LED and paper increases, and that the illumination on the paper from the laser pointer does not seem to spread out.

Part B, Step 3

Check on groups and assist as needed.

Part B, Step 5

Check on groups and assist as needed. (In the unlikely event that the students' illuminated spot is oblong rather than a circle, have them measure the longest and shortest distance across for each spot.)

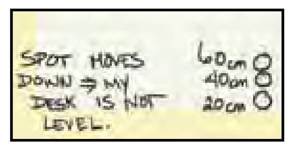
Part B, Step 6

Example data is provided

Have students make a table of their results, which could be on the paper they used to record their data. Sources of error might include pencil width, difficulty with measuring, and human error.

Part B, Step 7

Check student work. For the inexpensive lasers used in these lessons, the spot size may increase a bit; for a better-designed laser, the spot size should increase less.



Experimental note: In the example data provided here, the spot changed its location on the paper as the distance to the paper increased because the tabletop was not level.

Note about lasers: Lasers utilize mirrors to create a resonant cavity. The resonant cavity makes possible the intense, collimated beam. Some lasers may also include a lens. These devices and any apertures interact with the light, and hence the beam's width and collimation are limited by the laser's design.

Part B, Step 8

Have a class discussion on collimated light. Because the light in a laser beam travels in the same direction; it neither spreads out (diverges) nor comes together (converges). Point out that a perfectly collimated beam cannot be produced. If we try to put light through a small aperture it spreads out due to diffraction. **Let students know** that laser light is collimated because it is created in a cavity between two mirrors that allows light traveling in one direction to build up, (and it is coherent, but that hasn't been discussed yet).

If students are not doing the optional exploration below, then **demonstrate** to the class how light from a flashlight spreads differently than light from a laser. Simultaneously shine each light source on a wall while moving away from the wall.

Part B, Step 9

Have groups answer this and discuss their answers in a class discussion. Model the language that groups should use to respond to each other during the class discussion: I agree/disagree with ______ because _______.

Optional Enrichment Activity

How does light from a small light bulb spread out? Design and conduct an experiment with your group to measure how light from a bulb spreads out.

Notes on Optional Enrichment Activity:

If students are conducting this experiment with a bulb, and they hold their aperture too close to the bulb, then light produced from multiple points on the filament may make the edge of the shadow fuzzy.

Note: If students use a flashlight they would observe the spot of light on the screen spreading out substantially as the distance between the light source and the screen increased. If students use a bulb with no reflector, they should consider placing the bulb behind an aperture, such as a piece of cardboard with a 5 cm diameter circular cutout. They could also devise an experiment observing shadows made by an object at various distances from the light source.

Make sure students understand what collimated light is (light travels in one direction – light rays are parallel) and that laser light is collimated.

Did students reach the goal of Part B? Students should be able to state that laser light is very collimated (light rays are parallel) and provide supporting evidence for this. If you do the optional enrichment they should be able to say that laser light is more collimated than light from other sources, and provide some supporting evidence for this. Students should have some sense that the collimation of the light is due to the cavity (mirrors) of the laser.

Note: You may want to point out that lasers are not the only collimated light source. Light from great distances, such as the sun or another star, is considered collimated. Also, parabolic mirrors and con-

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?

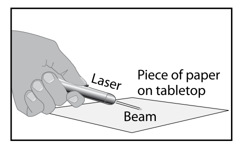


Image credit: Nancy Bennett-Karasik, @ American Physical Society

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vex lenses are often employed to collimate light. Mirrors are used in laser systems to help collimate the light.

C. Is there anything else special about laser light?

Notes on Student Edition, Part C

Have a discussion about what students think the answer to this question is, besides single wavelength (monochromatic) and parallel light rays (collimated).

Goal of Part C: To describe that laser light is coherent (light waves are in phase, or light travels "in step"), and provide some supporting evidence for this.

Students may say: They shine a really far distance; they don't get blurry and dim like flashlights.

Part C, Step 1

Students' drawings and descriptions should include an illuminated region with bright shimmering spots, and dark spots. There should also be an indication that the light is red.

Part C, Step 2

Students' drawings and descriptions should include an illuminated

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.

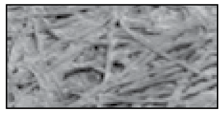
Image credit: Dr. Del Atkinson
Paper Fibers

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.

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region with a seemingly homogenous or averaged-out central area of red light, with a dimmer area of homogenous red light around the central area. Students should note that the red LED source does not produce the "sparkly" or "speckled" pattern that the laser light produces. For example they may state that the laser light produces tiny bright and dark spots in the illuminated area, whereas the LED does not produce these bright or dark spots.

Part C, Step 4

- **Have students** use two graphs of the sine wave and show how these waves would interfere as they enter the eye. For the bright spot the two waves enter the eye, in phase. For the dark spots the two waves enter the eye out of phase. Discuss with students what would happen when the two waves enter the eye at different angles. For example, hold the two waves together at one end, and about a foot apart at the other. Have students consider what the amplitude of each wave would be where they meet, and what the resulting amplitude of the combined waves would be.

- The brighter areas are caused by constructive interference, and the darker areas by destructive interference.

- **Let students know** that ordinary light is composed of many different wavelengths of incoherent or out-of-step light that is usually not collimated. When this type of light interferes, the multitude of light waves that interfere average out, resulting in a homogenous spot of light that doesn't show a speckle pattern.

NOTE you can create a speckle pattern from sunlight reflecting off of your fingernail! For more information conduct an internet search on "Science News for Kids, Speckle."

Part C, Step 5

Have a class discussion on coherent light.

Let students know that waves traveling in the same direction with a constant difference in phase are called coherent. Laser light is composed of coherent waves that are in-step.

Consider sharing this example: When many waves are of the same wavelength and in-step, they add up to make a very large amplitude wave. These waves are coherent. For example, if 100 waves of the same wavelength and amplitude all were in phase, they would add up to act as a single wave with 100 times the amplitude. The amplitude of the wave is related to the amount of energy the wave carries. As the amplitude increases the energy increases.

Have students draw a diagram showing how three identical waves that are in-step add up.

Students' answers should show the amplitude of the resultant wave being three times the amplitude of the initial wave.

Part C, Step 6

Have groups tell what they have learned in *Part C* and discuss their answers with the class. **Help the class** come to consensus on answering this question.

Did students reach the goal of Part C? Students should be able to describe coherence, state that laser light is coherent, and provide supporting evidence.

Make sure students understand that coherence means that the light waves have a constant relative phase, and that a special property of laser light is that it is coherent and in phase.

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

Notes on Completing the Lesson, Step 1

Laser light:
- has one wavelength (it is monochromatic or has one color)
- is collimated (parallel rays of light)
- is coherent (constant relative phase and in-step).

A helpful acronym may be the three c's or c^3: color, collimation, coherence.

Point out that laser light is very bright because of the property of coherence (constant relative phase and in-step), as well as for other reasons. Let students know that laser light can carry enough energy to burn through objects such as one's eye and sheets of metal. The first lasers (ruby lasers) used to have their strength discussed in terms of how many razor blades they could burn holes through. A one-Gillette™ (type of razor blade) laser did not have as bright a laser beam or deliver as much energy as a five-Gillette™ laser.

Optional: Show students the 4.5 minute video of Theodore Maiman explaining the first ruby laser, located on the LaserFest website found by conducting an internet search on "laserfest, Maiman video." This can be used as a transition to discussing what is needed for a laser to function (an active medium, an energy source, and a resonant cavity).

Notes on the kinesthetic model of different light sources

Goal of kinesthetic model: For students to have an experience that deepens their understanding of the special properties laser light.

For this model students represent photons (packets of light energy). Students' step length represents the photon's wavelength. Since the different colors of light have the same speed, the frequency of steps taken increases as the step length (wavelength) decreases. Simulate light from each light source using this model. Then have students describe how the model represented the light produced by the light sources.

Consider having the entire class participate for each type of light or having groups model each type of light.

Trouble-shooting: One issue that may arise is if the students try to walk with the same frequency rather than the same speed. If this occurs some students may say that blue light travels slower than red light, which is not the case. Remind students that because the index of refraction of air is so close to that of a vacuum, we consider that all light in the visible spectrum travels at the same speed in air. Consider having students representing different wavelengths walk side-by-side, holding a rod, if needed, to keep them side-by-side, while taking different sized steps so that they have the same speed. In this case the student representing violet light might take twice the steps the student representing red light takes. A suggested table of stride lengths is listed in the *Preparation before class* section of this lesson.

White LED: Place a red, orange, yellow, green, blue, or violet colored sticky or other indicator on students to show what color of light they represent. Each color will have a different stride length, red being the longest and violet the shortest. If you have a pattern on your floor you could devise a different stride length based on the pattern. If you do not have a pattern on your floor, use colored masking tape to represent the different wavelengths of light, as described in the *Preparation before class* section for this lesson. Have the students move away from the location you designate as the light source on the floor at the assigned stride lengths. This incoherent light source should have photons of all visible colors traveling at many different angles from the light source.

Red LED: Place a red, orange and yellow (and green if observed) colored sticky (or construction paper) on students to indicate what color of light they represent. Each color will have a different stride length, as before. Run the model as you did with the white LED, but in this case use only the observed colors produced by the red LED. You could try to represent the relatively dim yellow light that students saw through their diffraction gratings by having fewer students represent yellow photons than red photons.

Red laser light: Place a red colored sticky on each student to indicate the single color of laser light that they represent. Each student will move with the same stride length, and in step (perhaps five

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.

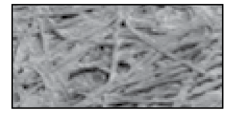

Image credit: Dr. Del Atkinson

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.

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students wide with elbows interlocked) like a marching band. Have the students move along a straight line between two objects that represent mirrors. Point out that the mirrors within a laser cavity help to collimate the laser light. **Let students know** that coherent laser light is caused by a special process, which they will explore in Lesson 2.

Teacher's Notes

Lesson 2. How Does a LASER Work?

Materials

- computer projection system
- computer(s) that can run the PhET simulator with simulator loaded onto each
- to find the PhET simulator, search on "*PhET Laser Simulator*" or go to http://phet.colorado.edu/simulations/sims.php?sim=Lasers
- projections of *Lesson 2* images
- masking tape
- sheets of paper (e.g. red construction paper)

Goal

Students should gain understanding about the fundamental parts of a laser and how they affect the output of the laser. The fundamental parts of a laser are:

- atoms or molecules (the active medium)
- an energy source
- a resonant cavity

Time: 60 to 80 minutes – Prior to students working with the computer simulation, 20 to 40 minutes is needed to discuss the parts of a laser and how it works. An additional 40 minutes is needed for *Parts A* and *B,* or these could be assigned as homework depending on computer availability.

Summary of Lesson 2

Students consider what causes laser light to have its special properties. They are introduced to the three essential parts of a laser: the active medium (atoms or molecules that transform the input energy into the output energy), an energy source, and a resonant cavity. Students revisit the concept of conservation of energy to support the need for an energy source. Students relate the resonant cavity to collimation.

Students then explore the role the active medium plays. They are introduced to the interaction of light and matter by absorption, spontaneous emission, and stimulated emission. Through participation in a kinesthetic model, students simulate the processes of absorption and the two types of emission. Students relate stimulated emission to coherence.

In *Part A* of this lesson, students explore the fundamentals of a laser using a computer model called the PhET simulator. Students investigate the laser using a single atom for the active medium, and observe how the three basic parts of the laser produce laser light.

In *Part B*, students explore how to construct a multi-atom laser with the PhET simulator in order to understand how the variables of the laser affect the lasing process. *Parts A* and *B* can be completed independently, as a group, or as a class activity.

Preparation before class

Familiarize yourself with the PhET laser simulator and prepare for the demonstration. Determine if you will have each group use a computer, a set of groups use a computer, or if the simulations will be teacher-led with the entire class participating.

Decide if students will do *Part A* and or *Part B* during class or outside of class.

Prepare the room for the kinesthetic models as was done at the end of *Lesson 1*, for the laser. Two objects will be needed to represent the mirrors that create the laser cavity. These objects could be walls or desks. The width of the cavity should be at least 5 students wide. The length of the cavity (distance between two mirrors) should be an integer number of steps, marked by tape or a pattern on the floor. A reasonable cavity distance for this model is about 10 steps.

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

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2. How does a laser work?

Facilitate a class discussion on students' initial ideas about what causes laser light to have its special properties. Encourage students to provide their reasoning. Record students' ideas as you may want to revisit these ideas at the end of this lesson.

An example of a discussion format with preconceptions is provided below (e.g. I agree/disagree with___because __).
Student 1: "I think there are mirrors in there because it bounces off stuff, a light bulb, and a battery."

Student 2: "I agree with Sabrina but I think that instead of a bulb there is a little lens inside."

Student 3 talking to teacher: "I think there is a tube or something that has something inside it that reacts. Something that is reacting to make the laser red, and the way it is positioned too."

Teacher discussing inquiry method: "Don't talk to me. I'm standing behind you to try to get you to talk to the class not me. … I want you to address the class, even if I've asked the question. I'm not trying to be rude."

Student 4: "We think that there are two lights reflecting toward each other and a mirror shooting the light out and making it stronger."

Laser Components

Keep this fast-paced, about 10 minutes.

Goal of Laser Components: Students should be able to state that a laser has three essential parts

- an energy source
- atoms or molecules that transform the input energy to the output energy (an active medium)
- and a resonant cavity.

Students are not expected to know the details of these parts by the end this discussion, but should make connections between the resonant cavity and collimation and realize that conservation of energy requires an energy source for the laser.

Review with students the special properties of laser light that you explored in *Lesson 1*.

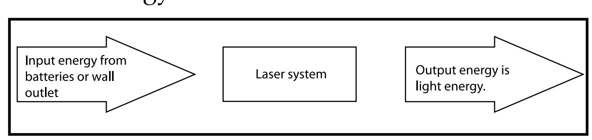
Color – monochromatic or single wavelength (or, equivalently, a single frequency), collimated, coherent

Have each group answer the question: What do you think causes these special properties of laser light? Be prepared to discuss your ideas with the class.

Students should be able to indicate that the mirrors in a laser help to collimate the beam. Let students know that they will later use a computer simulation to observe that the mirrors create the laser cavity and help build up the coherent light waves within the cavity. Some of these light waves emerge to produce the laser beam.

Students may or may not have an idea about how the single wavelength and coherence arise. This will be discussed before they start the computer simulation.

Have each group answer the following questions: Does a laser give off energy? If so, where does this energy come from? Have them describe or draw any energy inputs into the laser and any energy outputs from it. Tell them to think about conservation of energy.



If a group is having trouble, have them consider where a light bulb gets its energy or ask them about where the energy to operate the laser pointer they used came from.

Students should realize that the laser outputs light energy (and thermal energy) and is capable of producing a great amount of light energy in a single beam of light. Students should utilize the concept of energy conservation to support the idea that an energy input is required. Most students will realize that the laser pointer uses batteries as its energy input or energy source; others may mention electrical energy supplied from a wall outlet for a plug-in laser.

Make sure students understand that lasers require an energy source.

Have each group answer the question: What transforms the input energy into the output light energy of a laser? (Hint: Some popular lasers are the helium-neon laser, argon-ion laser, krypton laser, ruby laser, carbon dioxide laser)

Preconceptions: Students may have a variety of answers depending on their background knowledge. The hint in the previous paragraph should make them think of atoms or molecules, but they may need further hints. You could ask them what they think is in a helium-neon laser or an argon laser. What is similar about the two? Students may say gas, but encourage them further by asking what "gas" is made up of, and reminding them that ruby is also in the list and it isn't a gas.

Let students know that the input energy is eventually transferred to atoms or molecules within the laser system (in the laser cavity) and these atoms/molecules absorb the input energy. These atoms/molecules then emit light energy. The atoms/molecules transform the input energy into the output energy. The process by which this occurs will be discussed and modeled soon.

FYI: You could let students know that the atoms/molecules that perform this energy transformation can be in a gas, liquid, or a solid state. Scientists call these atoms/molecules the "active medium." The simulator students will use later has a gas as the active medium.

Make sure students understand that the atoms/molecules in the laser system transform the energy put into the laser system to the output energy. Let them know that scientists call these atoms/molecules the active medium.

Consider letting students know how electromagnetic waves are formed (a national standard). You could tell the class that electromagnetic waves (e.g., visible light waves) are created by a charged particle that is changing its motion or by a changing magnetic field. (For more information conduct an Internet search on "production of electromagnetic waves".) This may also be brought up again in *Lesson 3, Part 1* (optional) that discusses the application of the transportation of information via electromagnetic waves.

Summarize: The essential parts of a laser are
- an energy input or energy source, which is required by the law of conservation of energy,
- atoms or molecules that transform the energy source to the energy output (laser light),
- and a resonant cavity (or mirrors) which aid in the collimation (and build-up) of the laser light.

Introduce students to the term resonant cavity - a resonant cavity allows a standing wave to be formed. Let students know that the mirrors act as the resonant cavity, which allows a fixed number of wavelengths to go back and forth within the laser cavity. This helps in collimating the laser light, and also in building up the coherent light energy.

Goal of Laser Components: Students should be able to state that a laser has three essential parts-
- an energy source
- atoms or molecules that transform the input energy to the output energy (an active medium)
- and a resonant cavity.

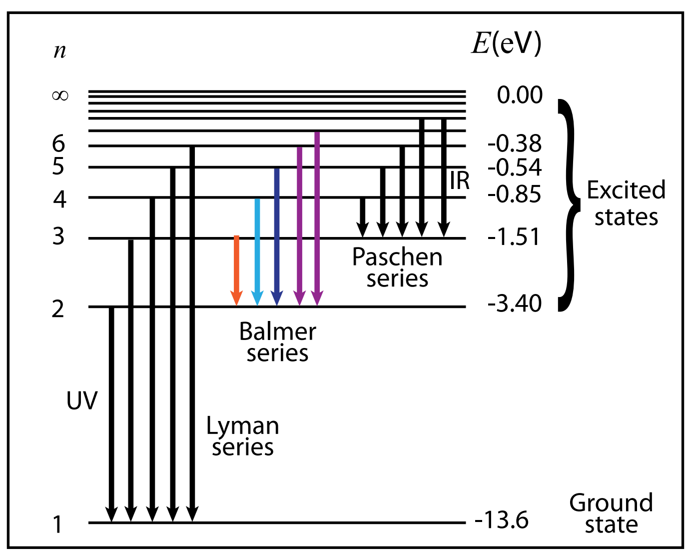
Students are not expected to know the details of these parts by the end this discussion, but should make connections between the resonant cavity and collimation and realize that conservation of energy requires an energy source for the laser.

Interaction of Light and Matter

Time: not take more than 20 minutes. To save time, you could skip having students draw the energy level diagrams.

Discuss atoms in the laser cavity: For simplicity, consider atoms in a gas that transform the input energy to the output energy. Have each group discuss how they think the atoms in the laser system transform the input energy to the laser's output energy. Have a class discussion with each group contributing their ideas.

Goal of Interaction of Light and Matter: Students should be able to describe absorption, spontaneous emission, and stimulated emission, and how the active medium transforms the energy put into the laser to the light energy that comes out of the laser. Students should be able to make connections between stimulated emission and coherence.



(Image credit: David Darling, http://www.daviddarling.info/encyclopedia/H/hydrogen_spectrum.html)

Point out that unlike everyday objects that can have a continuous range of energies (e.g., a soccer ball), an atom's electrons are allowed to have only certain distinct energies.

Let students know that when an electron moves from one allowed energy level to another it is called a transition. The pattern of an electron's allowed energy transitions are like fingerprints. Each element has its own distinct pattern of transitions. This pattern is used to determine what elements are present in stars, gases, and other substances.

Draw or project the first seven atomic energy levels of hydrogen on the board (see drawing on previous page) and show the five transitions from state "2" in the drawing (this is also called the first excited state).

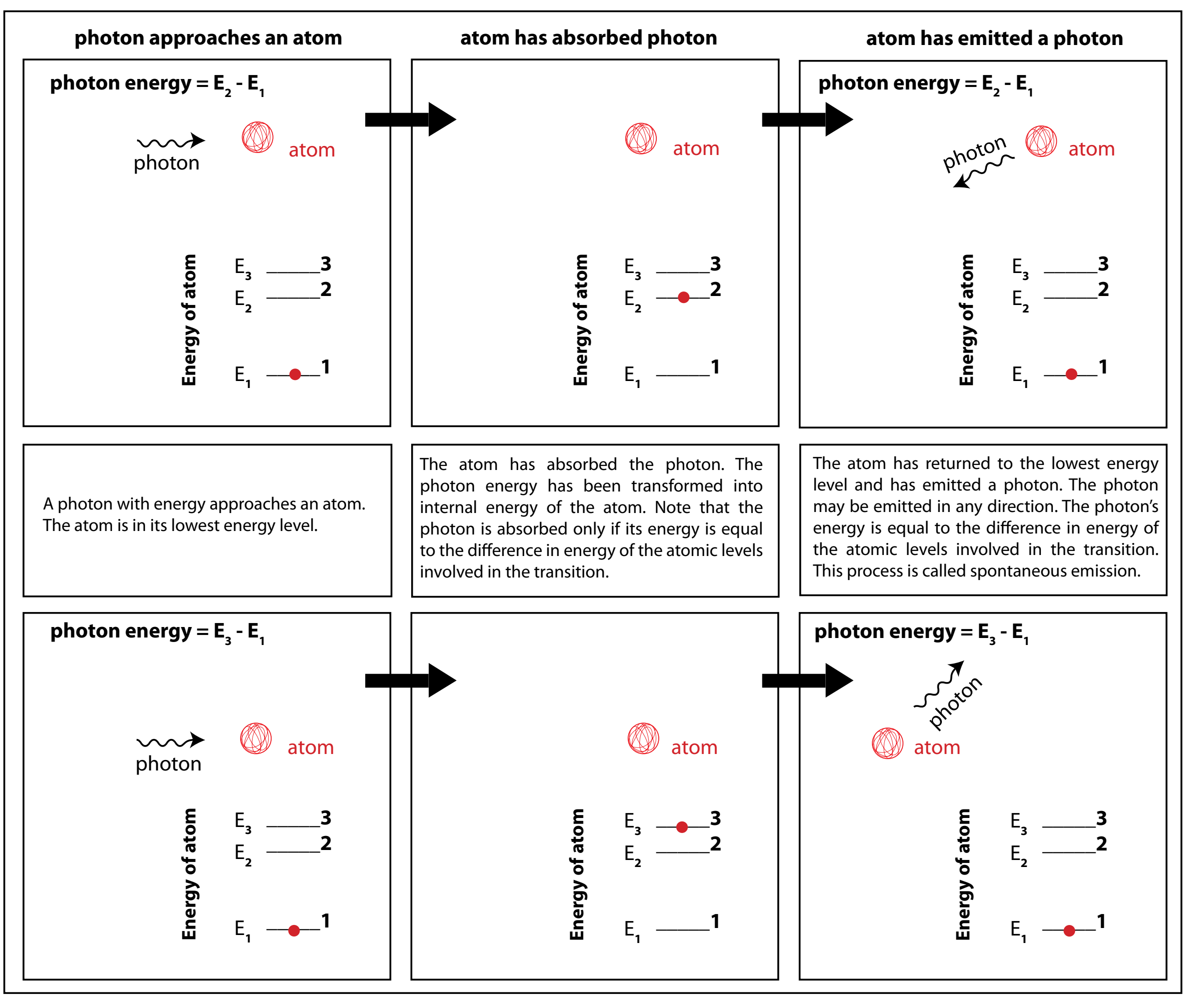
Show the students a color version of the spectrum ("fingerprints") of hydrogen, or even better, have students observe excited hydrogen gas through diffraction gratings. What are the colors of visible light in hydrogen's "fingerprint?" Point out the colors of the absorption and emission spectra and the transitions that they correspond to on the energy level diagram (Balmer Series: red, cyan, blue, violet)

Consider letting students know that an atom's electrons are only allowed in certain energy levels, and these energy levels are discrete or quantized. Scientists usually express the energy levels of an atom in units of electron-volts (eV). *1eV = 1.602x10*$^{-19}$ *Joules*. Students don't need to know the details of electron volts for this lesson, just that it is a unit of energy, which is also used in the PhET simulator.

Discuss absorption: when an atom's electron moves to a higher energy level, the atom absorbs energy, and increases its internal energy. This energy could be transferred to it by the absorption of a photon (light energy) of just the right wavelength (or frequency). Energy is conserved–the light energy was transferred to the atom, absorbed and transformed, increasing the atom's internal energy, as shown in the first two columns of the diagrams below. Display the first two columns below for the class

Discuss spontaneous emission: When an atom naturally decays to a lower energy state, it is called "spontaneous decay" or spontaneous emission. In this process some of the atom's internal energy is transformed into light energy. The light energy is emitted as the atom's electron moves from a higher energy level to a lower one. The emitted photon has a frequency proportional to the energy difference between the atom's two energy levels involved in the transition. Emphasize that the emitted photon may travel in any direction. The amount of time it takes for the atom to decay depends on the difference between the energy levels involved in the transition. The greater the energy difference, the faster the atom transitions to a lower energy state.

Absorption and Spontaneous Emission of a Photon by an Atom



Kinesthetic model for absorption and spontaneous emission

- explain model
- run model for absorption only
- run model for absorption and spontaneous emission
- discuss stimulated emission
- run model again with stimulated emission.

Let students know that in this model

- students participating in the model will represent energy, either as photons (packets of light energy) or as internal energy of the atom.
- a piece of paper will represent the atom. When the paper is on the ground the atom is in its lowest energy or ground state.
- the photons all have just the right amount of energy to be absorbed by an atom, causing it to move to a higher energy state.
- to express the absorption of the photon, and the increase in the atom's internal energy, the student stops moving and lifts up the paper (atom in an excited state).
- two walls (or desks) represent mirrors creating the laser cavity.

(Atomic "states" correspond to atomic energy levels.)

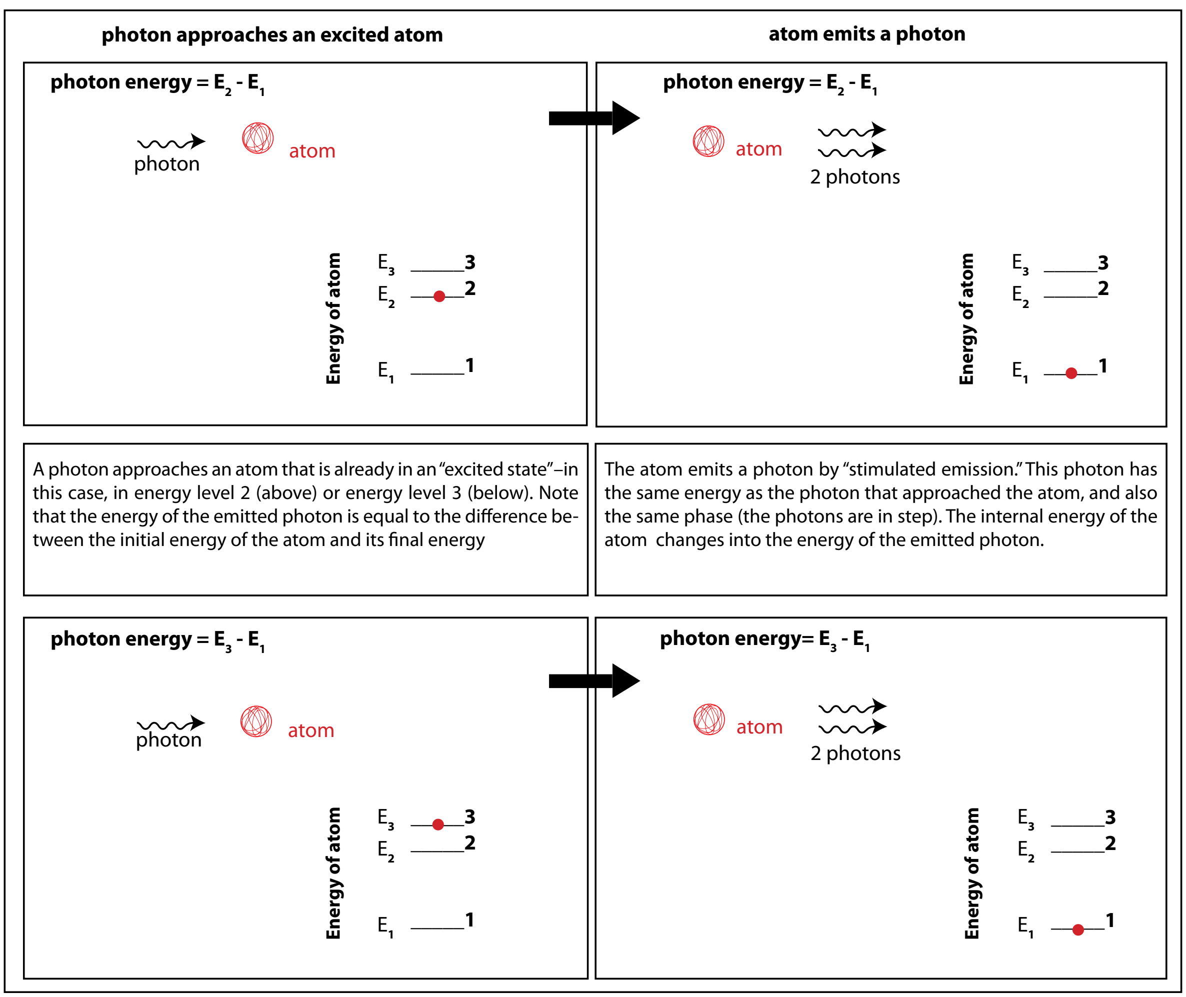
Run the kinesthetic model to simulate absorption of photons

- Have a cleared area on the floor, preferably where students had performed the kinesthetic models during *Lesson 1*.
- Place some sheets of construction paper on the floor.
- Let the students know that the construction paper on the floor represents atoms in their ground state.
- Then have a few students be photons. Label the students with different colors of light.
- Let the class know that only photons that are red are just the right frequency (meaning they carry just the right energy) to be absorbed by the atoms in this model. Then have photons travel to the atoms. All the photons but the red ones should walk straight to the other side of the room. The red photons should stop at the atom and lift up the construction paper to simulate an atom absorbing a red photon and increasing in internal energy.

If some red photons forget and walk straight through that is okay. Let the class know that realistically, not all the red photons would be absorbed by the atoms.

Remind students that the students represent energy in the model. Initially all students are photons (light energy).

Stimulated Emission



Some students that represent red photons are absorbed by the atom (paper) – after absorption, these students represent internal energy in the atom. The paper on the ground represents the atom in its ground state. The paper lifted up represents the atom in an excited state with increased internal energy.

Discuss the absorption and spontaneous emission. An atom is in an excited state when it has absorbed energy and is no longer in its lowest energy state. Excited atoms will naturally "decay" or go back to their ground energy state. When they do this, the atom "loses" internal energy, but where does the energy go? A photon is emitted. If the atom absorbed a photon of red light, and then naturally decays back to its original state, it will spontaneously emit a photon of red light.

Run kinesthetic model to simulate absorption and spontaneous emission of photons.

- Decide how many students you want to participate.
- Use pieces of construction paper on the floor to represent atoms.
- Number the students one through four.
- Review the absorption process by having students start as photons that will be absorbed by the atoms. Let the class know that only photons of just the right frequency (and hence energy) are absorbed by the atoms.
- Then have photons (students) travel to the atoms (construction paper).
- The photons (students) should stop at the atom (construction paper) and lift up the construction paper to simulate the absorption of the photon's energy and its transformation into the atom's internal energy.
- Students should count until they reach about twice their assigned number before the atom decays. When this occurs, the students should put down the construction paper to simulate the atom going to its ground state, and travel in **any** direction (in a straight line) across the room. **It is important to emphasize that there is no preferred direction in spontaneous emission.**

Consider having students answer the following questions: Describe what the students you observed represent. What does the paper represent? What does the position of the paper represent? Was there a pattern to the way the emitted photons traveled? If so, describe the pattern.

Remind students that in the model students represent energy (first light energy, then internal energy, and finally light energy again). The paper on the ground represents the atom in its ground state. The paper lifted up represents the atom in an excited state. The photons can be emitted in any direction. (Some students may say that the photons are emitted within a certain time frame.)

Emphasize energy. In this model the students represent energy – first light energy, then energy in an atom, then light energy again. It is important for them to follow the energy. Point out that realistically not all the photons would be absorbed, and that all the excited atoms would decay over a period of time.

Discuss and model stimulated emission

Introduce stimulated emission by letting students know that there is another type of interaction between light and an atom – a special one. Ask students to imagine an excited atom, one that has just absorbed a photon of red light, and suddenly another red photon comes by. Ask students what they think happens and briefly discuss their ideas.

Demonstrate and explain stimulated emission model with four students

Using this model, students will review absorption and spontaneous emission, and be introduced to stimulated emission.

- Have the construction paper in the middle of the room.
- Have a line of four students that represent red photons.
- Have all but one of the students (red photons) get absorbed by three atoms. Immediately send in the last student (red photon).
- When the last student (photon) reaches an excited atom (lifted construction paper), have the last student tickle the lifted construction paper. The student holding the tickled construction paper should put it down, transforming from internal energy within the atom to a photon (light energy), and lock arms with the incoming photon (last student).
- These two students become coherent photons, walking right next to each other, in step, and in the direction that the incoming photon (last student) was traveling in. The incoming photon is said to have stimulated the excited atom to emit a photon. Let the other two excited atoms decay spontaneously so that those students travel off in any direction.

Remind students of what each part of the model represents. Students are initially photons (light energy), then they are absorbed by the atom (paper) and transform into internal energy of the atom (paper lifted off ground). When the atom (paper) decays, the atom returns to its ground state (paper on ground), and the students (energy) transform from internal energy into light energy. **Emphasize that, as a result of stimulated emission, the two photons are completely in phase (coherent) and travel in the direction of the incoming photon that caused the emission.**

Run the stimulated emission model again with many students

Explain to the students that they are going to run this model again according to the following conditions:

- Students will initially represent photons (light energy of a given wavelength).
- Some photons (students representing light energy)

will be absorbed by the atoms (paper on the floor), and transform into internal energy within the atom. The atoms will be in an excited state (paper lifted off the floor).

- Some of the excited atoms (paper held up by student) will decay spontaneously so that some students may transform back into photons (light energy) and travel in any direction.
- Other atoms will stay excited. The students will remain as internal energy within an atom, until the atom undergoes a stimulated emission.
- Two walls will represent mirrors.

Disclaimer: Let students know that atoms usually decay spontaneously after a short amount of time, but in this model, in order to demonstrate what is happening within the laser cavity, we let the atom stay in an excited state for a prolonged period of time.

Run model

- Have the students be photons that will be absorbed by the atoms (paper on the floor).
- Have about 1/4 of the atoms decay spontaneously, making sure that at least two of the students are heading toward the walls that represent mirrors.
- As the photons reach a wall, they should turn around, moving along the marks on the floor from the previous lesson.
- When they reach an excited atom they should tap or tickle the lifted paper, and the student representing the internal energy in the atom should put the paper on the floor and then walk arm in arm, or side by side and in step, with the student that stimulated the emission.
- This should continue until all the atoms are in the ground state. (It should look something similar to a marching band between the "mirrors.")

Consider having students answer the following: Describe what you observed when your class ran this model. What did each part of the model represent?

Students should describe each part of the model. Make sure students do not confuse what they represent. They are not the atom, nor the electron, they are energy – initially light energy, then internal energy within the atom (paper), then light energy again. The paper represents the atom. The paper on the ground represents an atom in its ground state, and in the air it is an atom in an excited state. Emphasize that students walking in step or in phase are coherent photons (which could become three or four or more depending on how many excited atoms they pass by).

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

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How does coherence fit in? What does coherence have to do with a laser?

Discuss: When an excited atom undergoes stimulated emission (a photon of just the right energy goes by an excited atom and stimulates the excited atom to emit a photon of the same energy), the two photons are coherent and in step with each other. This coherence is one of the special features of laser light.

Emphasize that the mirrors create the resonant cavity and allow the build-up of coherent photons along one direction in the laser, causing a collimated coherent beam.

Ask: Based on what we've done so far, what do you now think the atoms in a laser do? With your group, come up with your best group answer to this question and support your answer.

Have a discussion about what students now think the answer to these questions are. Get the class to agree on the wording of their answer. Guide students to discuss how this fits in with a laser.

The atoms that make up a laser transform the input energy into the desired output energy. The goal is to get the atoms excited by hav-

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.

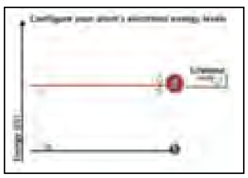

Image credit: PhET Interactive Simulations
University of Colorado
http://phet.colorado.edu

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?

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ing them absorb energy, and then to create stimulated emission. The more this happens the more coherent photons that are produced. Having coherent light (produced by stimulated emission) is an essential part of a laser.

Parts A and B of this lesson may be done by student groups, or independently outside of class. If you don't have enough computers available you could conduct *Parts A* and *B* as a teacher-led lesson, utilizing suggestions from the class.

A. How could you use a computer model to find out how a laser works? In this part of this lesson students will explore the PhET simulator and investigate how the variables of the laser affect the lasing process. Students gain evidence supporting the need for the three basic ingredients of a laser and the role that they play.

Goal of Part A: To make connections between the color of laser light and the allowed energy transitions of the active medium; the coherence of the light and stimulated emission; mirrors (resonant cavity), and the collimation of the light, and the buildup of coherent light within the laser. Students should know that stimulated emission requires the atom to already be in an excited state. Students should have a sense that it's easier to create a laser with atoms that have three energy levels.

More on the importance of using an atom with three energy levels: If we only had two energy levels, then the lamp photons that cause the atoms to be excited would also cause stimulated emission, but not in the direction between the mirrors of the laser (along the laser's axis). Usually the higher the energy level the shorter the lifetime of the level. Using the incident energy we can excite the atom from its lowest energy level to its third energy level, which rapidly decays to the second level. This second level has a longer lifetime and is responsible for lasing. As this intermediate level decays, some of the photons emitted will cause stimulated emission in the direction of the laser mirrors.

Students should be able to
- describe what the atoms in a laser do: absorption, spontaneous emission, and stimulated emission.
- describe how the atoms transform the input energy into the desired output energy of the laser.
- make connections between stimulated emission and coherence.

Let students know that the atoms (or molecules) used in a laser are called the active medium.

Tell students: The word LASER is an acronym that stands for Light Amplification by Stimulated Emission of Radiation.

Part A Step 4
Note that the incoming light supplies the energy that is absorbed by the atoms within the laser (the active medium).

To make the lamp increase the number of photons it outputs (or its intensity) slide the slider directly under the label "lamp control," to the right.

Part A, Step 6
Changing the allowed energy levels changes the energy that can be absorbed by the atoms in the laser, and the energy emitted by the laser. The energy levels determine the laser's output wavelength and energy.

Part A, Step 7
The longer the lifetime (slider moved to the right), the more time it takes before the atom spontaneously decays. During spontaneous emission the electron goes from the excited state to the ground state and emits a photon in any direction.

Part A, Step 8
Decreasing the lifetime causes the spontaneous decay to occur more rapidly. Students should observe photons emitted during spontaneous decay traveling in a different direction than the incoming light being absorbed by the atom.

Part A, Step 9

Students should observe that the atom undergoes absorption and both spontaneous and stimulated emission. However, eventually all the energy leaves the system through spontaneous emissions in directions not along the axis of the laser. Without a constant source of energy, the laser system cannot build up coherent, collimated light.

Part A, Step 10

The top lamp (purple light source) excites the atom to the third level. The atom undergoes spontaneous emission to the second energy level. The red lamp causes stimulated emission in the atom, or the atom spontaneously decays to the ground state. The process repeats.

Part A, Step 11

When the mirrors are put into the system the red lamp is turned off. Students should note that the red light eventually becomes coherent and collimated along the axis of the laser (between the mirrors).

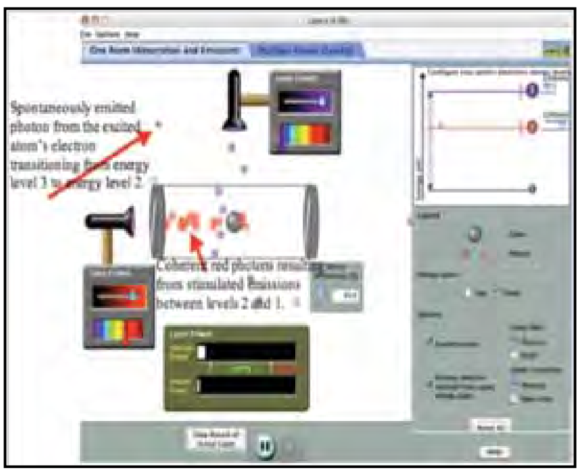

Image credit: PhET Interactive Simulations, University of Colorado, http://phet.colorado.edu

Part A, Step 12

Utilizing three levels of the atom for a laser provides scientists with the ability to create a significant build-up of energy within the laser cavity. Here's why and how:

- First, the higher an atom's energy level, the more quickly the atom will spontaneously decay to a lower energy level. This reduces the chances for stimulated emission to occur. The PhET simulator models this with the third energy level having a very short lifetime. By having the energy source excite to the third energy level, the intermediate energy level used for the lasing process can be quickly populated, since the third level quickly decays.
- Second, the atom spontaneously decays from its second energy level to its lowest energy level slowly enough that stimulated emission can occur. When a spontaneously emitted photon from the second level to the ground state is emitted in the direction of the mirrors, it can then go back and forth between the mirrors and stimulate the emission of coherent photons that will eventually become the laser output.
- Third, if the input energy were the same as the output energy, the stimulated emission process would occur along the same direction of the incident photons. You can demonstrate this to the class by setting the PhET simulator for a single, two-level atom, no mirrors, and the lamp turned on high. The amplification is in the direction of the incident photons, and the amplification would not produce a significant build-up of energy, but there would be an increase of coherence.

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).

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Part A, Step 13

Have the students summarize how the PhET simulator works and how it corresponds to the essential components of the laser.

Example: The lamp provides the incident photons that are absorbed by the atoms in the cavity. The atoms transform this input energy to the output light energy. The atom's energy levels determine the incident photon energy needed (in the PhET simulator), and also the energy of the laser output photons. The mirrors, which form the cavity, help to build up the coherent radiation that is caused by stimulated emission, and they help to collimate the light.

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.

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NOTE: Many lasers do not use a lamp to excite the atoms or molecules, but rather use an electric discharge to excite the atoms or molecules into various energy states.

Part A, Step 14

Example: The energy source provides energy to be transformed to laser light. The active medium (atoms/molecules) transforms this energy into single wavelength (monochromatic), coherent light energy. The resonant cavity (mirrors) help to collimate the light and build up the coherent light.

Did students reach the goal of Part A? Students should be able to make connections between 1) the color of laser light and the allowed energy transitions of the atoms in the active medium; 2) the coherence of the light and stimulated emission; 3) mirrors (a laser cavity) to assist in collimating the light and building up the coherence of light. Students should know that stimulated emission requires an atom to be in an excited state. Students should have a sense that it's easier to create a laser with atoms that have three energy levels, which allows the atom to be in an excited state long enough for stimulated emission to occur.

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

Part B Goal: Students should be able to set the simulator variables to get it to lase.

Individuals, groups, or the class determine how variables within a laser affect the process of lasing for a multi-atom system. You may also have students determine how to get the laser to self-destruct.

If you only have one computer available, lead the class through the exploration.

Part B may also be assigned as an out-of class activity if students have computers available to them.

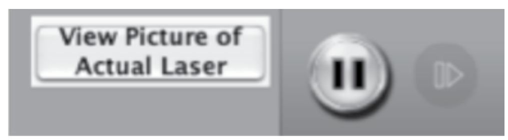
Part B, Step 1

Check to see that students can explain how they chose their initial settings of the variables.

Part B, Step 2

Students should record their observations. Based on their observations students should record any changes made and their reasons for making those changes.

Encourage students to view the actual laser through the link in the PhET simulator. The button for this is at the bottom of the window. Pushing this button brings up the pop up window shown below.



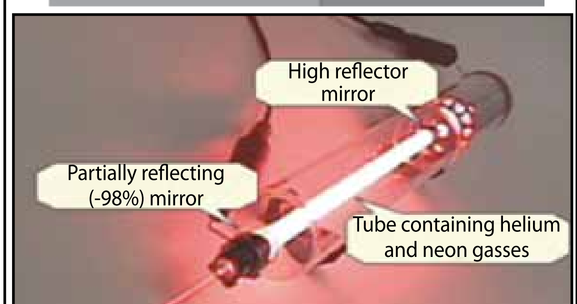


Image credit: Meredith Instruments

Atoms in a laser can be excited either by light, as in the simulation, or by collisions with energetic electrons (like what happens in a florescent light). The helium-neon laser shown here is particularly photogenic, but it excites the atoms with energetic electrons produced by having an electrical discharge through the gas. The discharge is produced by applying a voltage between the ends of the tube of gas via the two wires in the picture.

An example of how the PhET simulator could be set up to create lasing is shown on the following page. The laser will lase over a range of wavelenths corresponding to the range between red and blue.

Guidelines for variable settings:

- Use the Multiple Atoms (Lasing) tab
- Select three energy levels
- Maximize level two's lifetime
- Match lamp output energy to energy between levels three and one
- Enable mirrors, and set mirror reflectivity to 96%
- Adjust slider for lamp intensity so that level two's population is maximized

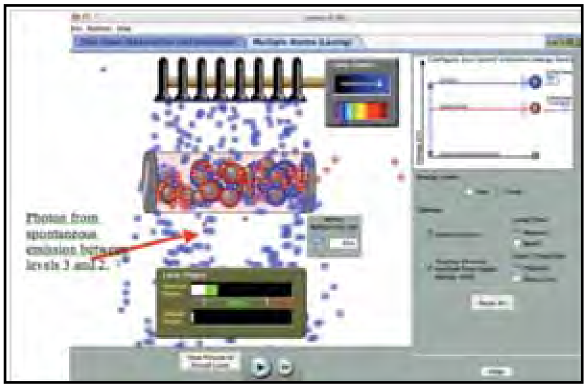


Image credit: PhET Interactive Simulations, University of Colorado, http://phet.colorado.edu

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

Part B, Step 3

An easy way to achieve this is to have the same laser settings as those that worked for *Step 2*, but now make both mirrors 100% reflective.

Part B, Step 4

Students should indicate that an energy source is needed to initially excite atoms that make up the active laser medium. The active medium transforms the incident input energy into the laser output light energy. Mirrors are needed to collimate this light energy and allow it to build up. From the PhET simulator students should recognize that the active medium is composed of atoms. The atom's energy levels used in the lasing process must have a long enough lifetime to allow for stimulated emission to

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.

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occur. Students might have a sense that it is easier for this process to occur with multi-level atoms making up the active medium.

Did students reach the goal of *Part B*? Students should have adjusted the variables in the PhET simulator using the multi-atom, three-level settings, to obtain the lasing process. Their answer in *Part B, Step 4* should describe the conditions they needed to get the PhET simulator to lase.

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

Teachers Notes

Lesson 3. What are Some Applications of LASERs?

Goal: Students should be able to describe some laser applications, and give examples of how science and technology can affect society.

Time: 20 to 40 minutes – ½ to 1 class period.

Summary of Lesson 3

Through hands-on experiences students explore several laser applications. *Part A* of this lesson is an optional activity[1] that has students investigate one way in which information can be carried by light. Students transmit sound on a laser beam and use a solar cell as the receiver.

Students determine the width of their hair in *Part B* using the diffraction pattern formed by shining a laser pointer on a strand of their hair. Criminalists, scientists that analyze evidence from crime scenes, use lasers to analyze evidence collected. (Although most measurements of hair thickness are done with microscopes, forensic technicians use lasers to collect evidence at the scene of a crime.)

Students read about the evidence provided by X-ray diffraction for the helical structure of DNA in *Part C*. Students build a model of X-ray diffraction by DNA using a laser and helical spring. This laser application helps students understand how diffraction can be used to determine the structure of an object.

In the last part of this lesson students explore laser speckle and read about how it is used to measure blood velocity.

To find information on applications and research involving lasers, explore the American Physical Society's outreach website Physics Central.

Safety

Lasers are powerful light sources that can cause permanent eye damage. If a student stares deliberately into a laser beam, permanent and irreparable eye damage can occur. Because of this, it is suggested that students use a Class II laser. Class II lasers are no greater than *1 mW* and the blink reflex will prevent eye damage, unless deliberate staring into the beam occurs. Most laser pointers are Class III A lasers, which are up to *5 mW*. Class III A lasers can cause permanent and irreparable eye damage if they are used with lenses or mirrors or if direct viewing of the beam occurs. Direct viewing of the beam off of highly reflective surfaces such as mirrors will also cause permanent and irreparable damage. The National Science Teachers Association recommends that students below high school level should not handle laser pointers; rather the teacher should perform demonstrations with the laser pointer.[2] Additionally, it is suggested that safety posters be displayed in the classroom when using lasers. If conducting the optional *Part A* of *Lesson 3*, review the safety issues involved with the different classes of lasers. The Spectra Sound kit includes in it a Class III A laser. The safety information for lasers can be found online by conducting an Internet search on "laser safety".

Materials

- 1 spring per group
- 1 laser pointer per group
- 1 slide holder per group
- tape
- 1 meter stick per group
- 1 metric ruler per group
- 1 sheet of white paper per group
- optional: 1 box or box lid per group

Materials for optional part carrying sound on laser light *(Suggested purchase: the Spectra Sound kit (below cost) through Physics Central http://www.physicscentral.com/)*

- 1 white LED
- 1 pen laser (Laser Lesson kit laser can be used)
- 1 headphone jack with stripped wires
- 3 AAA batteries and battery holder
- 1 *1000 μF* capacitor
- 2 alligator clip wires
- 8 B connectors or other wire connectors
- pliers if using B connectors
- powered speaker such as a computer speaker or a stereo with an Aux input
- a music player such as an iPod or any MP3 player (Tests showed that the SanDisk Sansa and the latest iPod shuffle are not compatible with the Spectra Sound kit. It has been successfully tested with the Apple iPod, iPod Nano and the iPhone.)
- Solar cell connected to headphone jack with ends of wires stripped
- Computer speaker or a similar device with an auxiliary output jack.
- Optional: flour or baby powder.

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

[2]Roy, K. (2007). *Shedding Light on Laser Pointer Safety*, Science Scope, Summer 2007

Preparation before class

Conduct the explorations to become familiar with the apparatus and the difficulties your students might have.

If you plan on having your students investigate how sound is carried by light (*Part A*), then put together the Spectra Sound kits in advance. In addition to the instructions in the Spectra Sound kit, we list a set of suggestions on how to put together the circuit.

- Consider using a Class II laser.
- Do not tape down or use a rubber band to hold down the button of the laser. Students can depress the laser button when they need to turn it on.
- Follow the procedure below and solder the wires in the B connectors together.

1. Gather the equipment you need to make a transmitter and a receiver. 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. Connect the microphone jack with the solar panel (the receiver) into the AUX input of a speaker or stereo system. The photodetector you will be using in the receiver converts light into electrical energy.

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. You should hear a clicking sound each time you turn the white LED light on and off.

3. To build the transmitter, remove the back of the laser and the laser's batteries.

The following diagram will be used in the next three steps:

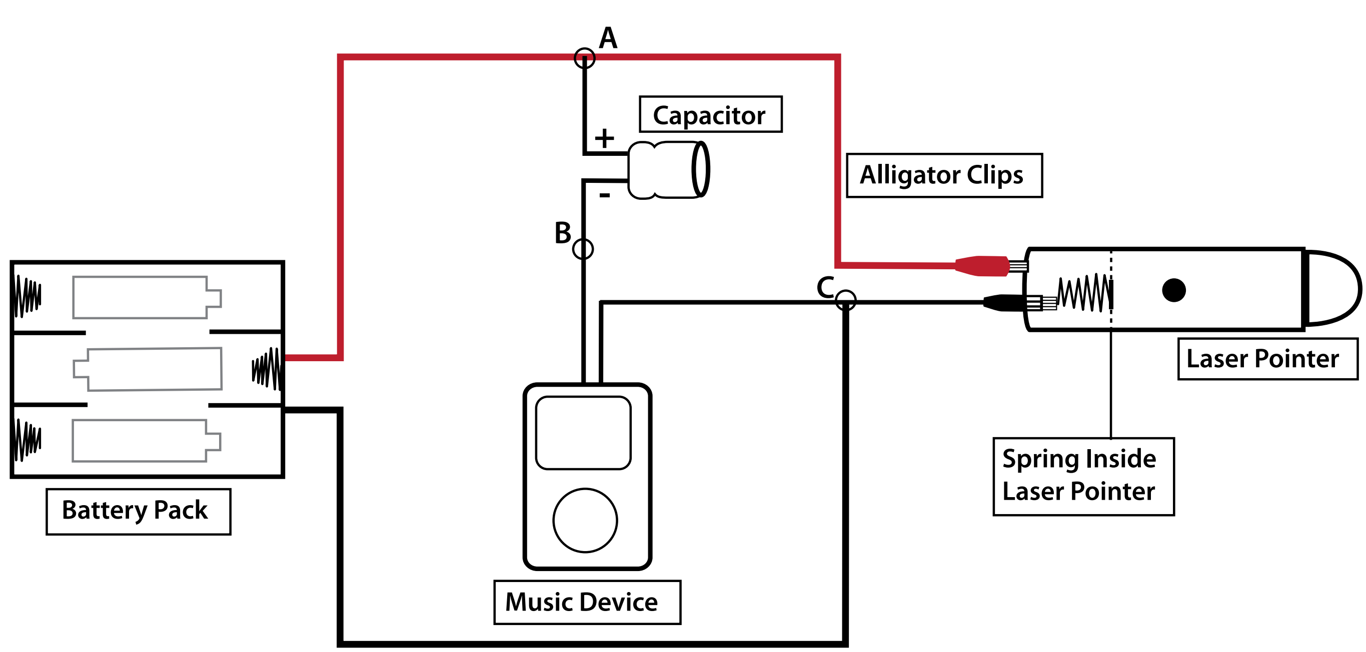
4. At point A on the drawing above, connect the following three wires: the red lead from the battery holder, the positive lead from the *1000 μF* capacitor, and the red wire from an alligator clip. You can use a B connector supplied with the Spectra Sound kit, or you can solder the wires together.

5. At point B, connect the following two wires: the negative lead from the capacitor, and one wire from the headphone jack (which plugs into the music device). You can use a B connector supplied with the Spectra Sound kit, or you can solder the wires together.

6. At point C, connect the following three wires: the black wire from the battery holder, the other wire from the headphone jack, and the black wire from an alligator clip. You can use a B connector supplied with the Spectra Sound kit, or you can solder the wires together.

7. Go to *Part A, Step 3* of the student version and go through the students' steps to make sure the system is functioning and to familiarize yourself with the equipment and how students will be using it. When you are done, remove the photocell from the wall.

Assembly Diagram



3. What are Some Applications of LASERS?

Introductory Questions

Have a brief class discussion on what students know about laser applications.

Describe some of the many uses of lasers.

- Reading bar-codes (see below for more information)
- Reading and writing CDs, DVDs and Blu-ray™ disks
- Communications, for example, sending Internet, telephone, and television/movie signals through fiber-optic cables (in some cases, right inside your home)
- Cutting things, from hard metals to soft tissues in the eye
    - ◊ In surgery laser cutting is considered better than a surgical knife because the laser cauterizes the wound as it cuts. Cauterizing means that it burns as it cuts which stops bleeding and helps to prevent infection.
- Measuring distances: from within an atom (*7 fm* for the halo of the Be nucleus), to distances in a house under construction, to the distance from Earth to the Moon (*384,403 km*)
- Measuring the speed of cars and blood cells
- Investigating how energy is produced in a star (conduct an Internet search on the National Ignition Facility).
- Collecting evidence at a crime scene or accident scene
    - ◊ Forensic technicians or criminalists use lasers in gathering evidence. For example, lasers are used to measure distances, and to find fibers, hairs, fingerprints, and other samples. Three-dimensional laser scans of crime scenes or accident scenes can reproduce every detail of the scene, accurate to within a few millimeters, and miniature models can then be constructed. Lasers are also used to determine where shots may have originated (bullet trajectory projections), and to determine molecular compositions of substances.

Bar code information: Laser light shines on an object with a barcode. The light that bounces off of the object is detected by a photodiode. The amount of light that bounces off and enters the light detector (photodiode) depends on the color of paper (or plastic) it is bouncing off of. White objects reflect far more light than black objects, for example. This difference in absorption of the laser light creates a change in the amount of light that bounces off the object and is detected by a photodiode or photocell in an electric circuit, which causes a change in voltage or current. Some laser scanners use a mirror or a rotating prism to scan the laser beam back and forth across the bar code.

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

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More information on laser applications can be found on the Internet by doing a search on the following key words, "laser applications". For video conduct an Internet search on "laser applications, video".

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

Check that groups are discussing ideas and consider having a class discussion.

Goal for Part A: For students to explore and describe how laser light can be used for communication.

Part A, Step 1

Lasers are used to carry encoded digital data along fiber optic cables. However in this exploration students will encode information by modulating the amplitude of the laser light.

FYI: Radio waves are used for wireless transmissions (such as from cell phone towers to the cell phone and wireless internet connections). The radio wave is created by an accelerated charge (e.g. in an alternating current circuit). As it travels it collects and deposits the information by interacting with a conductor (an antenna). When the

[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.

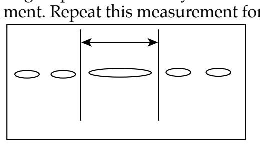
2. What do you think happens when you shine a laser beam at a strand of hair? Collect a strand of hair from several group members. Tape the strands of hair to the slide holder.

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.



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electromagnetic radiation interacts with a conductor it travels along the conductor's surface and induces an electric current on the surface of the conductor. Consider having students try out the PhET simulator on antennas.

The laser in the Spectra Sound kit is stronger than the laser in the kit used with this lesson. You could use the laser in the kit provided with these lessons as well. **Review** the safety requirements for the laser the students are using.

Part A, Step 2
Students should hear a clicking sound each time they turn the white LED light on and off. By turning on and off the light source, students are modulating the amount of the light reaching the solar cell. This in turn modulates the voltage produced by the solar cell.

Part A, Step 3
Students should observe that when the laser beam intermittently illuminates the solar cell, a clicking or scratching sound is produced. The sound is very loud because of the large and abrupt change in light intensity on the solar cell, as the beam is repeatedly interrupted. Correspondingly, this produces an abrupt and large change in voltage supplied to the speaker.

Part A, Step 4
Students should recognize that when the comb is run through the laser beam it is like rapidly turning the laser on and off. They should observe a clicking or scratching sound as the beam shining on the solar cell is interrupted with the comb.

Part A, Step 5
Students should observe that when the laser light shines upon the solar cell, the songs playing on the audio device (transmitter) can be heard through the speaker of the receiver.

Part A, Step 6
You may want to point out that most information carried on light waves is transmitted digitally, which is different than modulating the amplitude or frequency of a wave.

Part A, Step 7
Students should hear the song being turned on and off as the laser beam carrying the information is interrupted.

Part A, Step 8
Have a class discussion on students' ideas. Students may recognize that air is turbulent and has particles in it that can alter the amplitude of the signal being transmitted. You may want to demonstrate what happens to the transmitted signal when a powdery substance such as flour or baby powder interrupts the beam, by sprinkling a small quantity in the beam. Demonstrate this for students and have them sit far enough away so that they do not get particulate matter in their lungs.

B. How thick is your hair?
Check group responses. Consider having a class discussion on group's ideas.

Part B, Step 1
Discuss diffraction as needed: When waves have to go around objects or through small openings, they diffract (spread out). The diffracting waves can interfere, causing what is known as a diffraction pattern. For example, when light waves go through a single narrow slit, the light waves can interfere and produce a diffraction pattern on a screen like the one shown to the right of the diagram.

Show a projection of this image to the class.

Let students know that scientists determined the mathematical relationship shown in the diagram.

Describe the diffraction pattern shown to the right of the diagram.

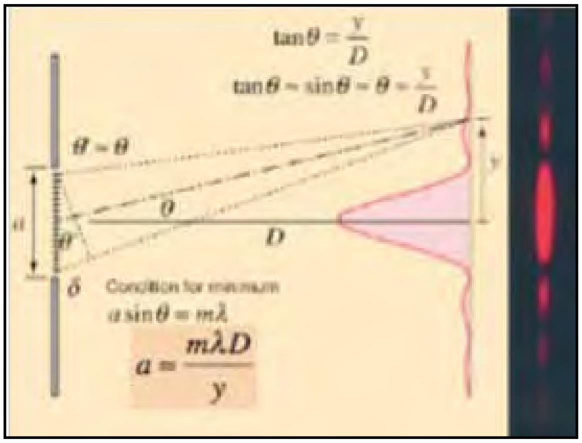


Image credit: From http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/sinslit.html

Students should note that the central bright spot is larger than the other bands of light or dark, and that the pattern is made up of alternating light and dark bands.

Part B, Step 2

Check students' responses.

Part B, Step 3

Make sure students stabilize the screen by placing it against a solid object, like a book or on a wall. Students should also make sure the laser is stabilized. Students should not try to hold the laser steady in their hand; instead they should place the laser on the desktop or on a book and shine it at the strand of hair.

Part B, Step 4

Students should note that they do not see a shadow of the hair but instead they see a diffraction pattern. The diffraction pattern would look the same as the diffraction pattern produced through a thin slit! (Consider asking: Why isn't there a dark shadow produced in the middle? Doesn't the object block the light? To learn more look up Babinet's Principle and conduct some other experiments.)

Students should obtain diffraction patterns like the one shown. If students have trouble seeing this pattern, have them shield the screen from the ambient light by placing the screen in a box.

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.

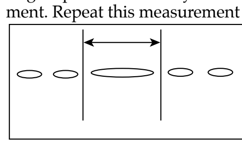
2. What do you think happens when you shine a laser beam at a strand of hair? Collect a strand of hair from several group members. Tape the strands of hair to the slide holder.

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.



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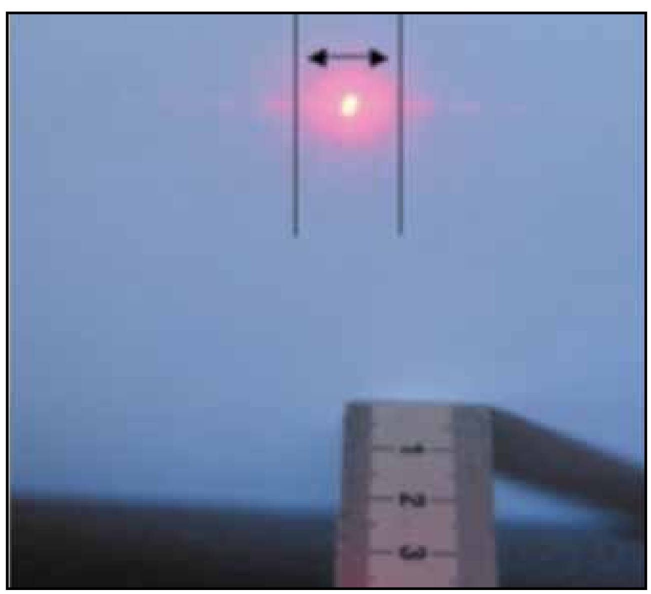
Part B, Step 5

For the strand of hair we used, the distance between the centers of the first dark fringes, or to the average distance between the edges of the dark fringes, was measured to be *1.5 cm* or *0.015 m*.



Photos by Ken Cole/APS

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	• tape
• spring	• 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.

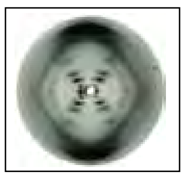


Image credit: Reprinted by permission from Macmillan Publishers Ltd: *Nature* 171, 740-741, © 1953

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Part B, Step 6

Head hair is usually between *50* to *180 microns*. Fine hair is *50 microns;* medium hair is *60* to *90 microns*; coarse hair is *100* to *180 microns*. Arm hair, or other finer hairs may be measured between *20 microns* to *50 microns*. Typically black hair is thicker than red hair, and red hair is thicker than blond hair.

Blond hair sometimes has unusual results because the laser light may go through it (it may be transparent to the laser light) and it may also cause a lensing effect. Curly hair may give various readings because of its shape.

Other hair facts: Hair becomes thicker with age. Hair is thicker the closer it is to the root. Hair's diameter increases with warmer weather.

Part B, Step 7

The formula the students are using in the steps that follow is:

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

For the strand of hair we used, the distance between the centers of the first dark fringes, as shown in the drawing above, was measured to be *1.5 cm* or *0.015 m*. Half of this is *0.75 cm.*

The denominator is divided by two because the quantity measured is twice the distance from the central maximum to the middle of the first dark band.

Part B, Step 8

On the laser pointer used in this example the range listed is *630 nm* to *680 nm*. The average is

$$\text{average} = \frac{630\text{nm} + 680\text{nm}}{2} = 655\text{nm}$$

Part B, Step 9

$$\text{width of hair} \approx \frac{(1)(655\text{x}10^{-9}\text{m})(1\text{m})}{(0.015\ \text{m}/2)} = 8.73\text{x}10^{-5}\text{m} = 87.3\text{x}10^{-6}\text{m} = 87.3\mu\text{m}$$

or 87.3 micrometers (0.0000873 m).

Part B, Step 11

See comments under *Step 6.*

Part B, Step 12

Example:

$$\textit{Number of hair strands in } 1\text{mm} = \frac{0.001\ \text{m}}{87.3\ \text{x}10^{-6}\ \text{m}} \approx 11.5$$

Arm hair is usually of the order of *20 microns (0.00002 m).* How many arm hairs could fit in *1 mm*? About 50.

Part B, Step 13

Check group responses. Students should describe how light diffracts around thin objects and that this can be used to measure the thickness of the object blocking the light. It is not expected that students will have a deep understanding of diffraction from this exploration. Diffraction patterns can also be used to measure the width of a thin slit, or the wavelength of light.

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

Hold a class discussion on groups' responses.

If students bring up X-ray lasers let them know that you can discuss this later, but it is not the point of this part. At the end of this part, if you have time, you could share with students that X-rays were discovered in the late 1800's by Wilhelm Röntgen. Non-scientists typically associate X-rays with the study of bones, but scientists often associate X-rays with the study of molecular structure through the use of diffraction. Visible light lasers were developed in the 1960's, but X-ray lasers were first predicted in the 1970s, and realized in 1984. The first laboratory demonstration of an X-ray laser was Nova at Lawrence Livermore Laboratory. Nova uses a high-energy light pulse (about a nanosecond in duration) to cause lasing at X-ray frequencies, but it can only be fired about six times a day due to the heat it produces. It is used to study plasmas.

Part C, Step 1

Check to see if students know that DNA has a helical structure. Consider having a class discussion.

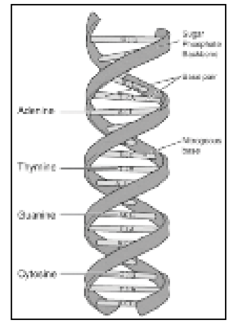


Image credit: Wikimedia Commons

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.

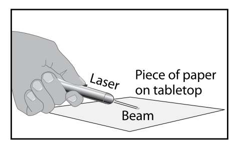
5. How is shining laser light at a spring similar to making an X-ray diffraction of DNA? With your group answer the question. Record your answer.

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.

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Part C, Step 4
Students should observe an "X" pattern on the screen. The arms of the X show a diffraction pattern with bright and dark fringes.

Part C, Step 5
Check students' responses. X-ray diffraction was used to provide evidence of the helical structure of DNA. Students should note that similar diffraction patterns—bright and dark bands along each arm of the "X" were produced using the model of a laser shining on a spring.

Part C, Step 6
Students should describe how the laser and spring model they constructed show that diffraction patterns provide information about structure. They should note the "X" pattern and the bright and dark bands produced along each "arm" of the "X".

You might want to tell students the following:
To better understand how the "X" diffraction pattern is observed, consider that the laser "sees" the spring as two crossed metal wires. One wire extends from bottom left to top right, and the other from bottom right to top left. As the laser beam is diffracted by the spring it produces a pair of patterns, one from each spring segment. Each pattern is similar to the pattern made by a human hair in *Part B* of this lesson. These two crossed diffraction patterns form the "X" diffraction pattern observed.

D. What can speckle patterns be used for?

Check that groups are discussing ideas, and consider having a class discussion.

Part D, Step 1
Students should describe a pattern of bright and dark spots as they did in *Lesson 1*. This is due to the constructive and destructive interference that occurs between the light reflected off of the paper. You may want to refer students back to *Lesson 1* and the picture of the paper fibers.

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.

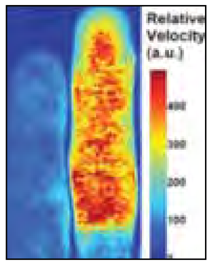

Image credit: Michael Smith, Institute for Biodiagnostics, Winnipeg, Canada.

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.

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Part D, Step 2
Students' descriptions should include a movement or shimmering of the speckle pattern as the students move their heads. The movement of the head moves the position of the detector (eye) and changes the path length of the rays of light entering the eye, thus changing the speckle pattern. The apparent movement of the speckle pattern has to do with where your eyes naturally focus on the speckle pattern and parallax.

Part D, Step 3
Students' descriptions should include a movement or shimmering of the speckle pattern.

Part D, Step 4
Students should observe a shimmering or changing speckle pattern, and provide reasons why they think this happens.

Students should note that the speckle pattern changes, as it did when they created a speckle pattern on paper and moved their head or the paper (in *Steps 2 and 3*).

The speckle pattern changes due to tiny muscle movements and blood flow under the skin.

Part D, Step 6
Have a class discussion on students' ideas. Students should include that laser speckle can be used as a fast and noninvasive way to measure the speed of blood flow near the skin, which could have many medical applications. Encourage them to present other ideas and consider how these ideas could be proved as feasible or unfeasible.

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".

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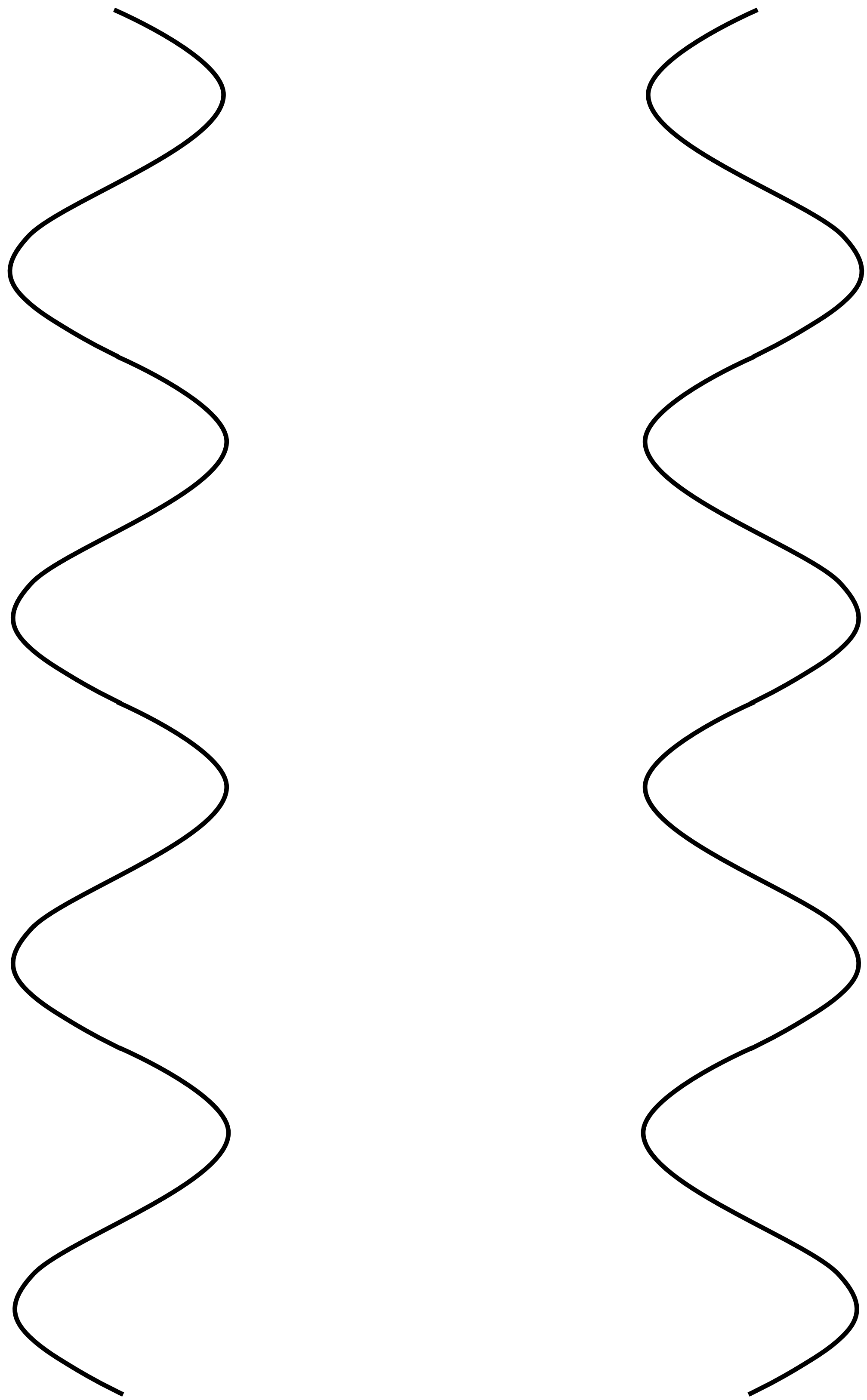
Teacher's Notes

Teacher's Notes

Sine Waves



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