SUPERCHARGED SCIENCE

Unit 9: Light

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Appropriate for Grades:
Lesson 1 (K-12), Lesson 2 (K-12)
Duration: 15-30 hours, depending on how many activities you do!

Energy can take one of two forms: matter and light (called electromagnetic radiation). Light is energy in the form of either a particle or a wave that can travel through space and some kinds of matter, like glass. We're going to investigate the wild world of the photon that has baffled scientists for over a century.

Table of Contents

Materials for Experiments

How many of these items do you already have? We've tried to keep it simple for you by making the majority of the items things most people have within reach (both physically and budget-wise), and even have broken down the materials by experiment category so you can decide if those are ones you want to do. *NOTE: This material list is for the entire Experiment section online.*

Light Waves

- Water glass
- Clean pickle jar
- Cooking oil, such as canola (approx. 4 cups – use a cheap brand)
- Two pennies, dollar bill
- Flashlight
- 1 teaspoon of milk (soy, cow…) OR white flour
- 2 hand held magnifying lenses
- Old CD you can scratch (used in two experiments)
- Paper towel tube
- Feather (any size)
- Index cards
- Crayons
- Bar of Ivory soap (get a pack of 3)
- Sharp pencil
- String (about 3')
- Scissors, tape
- Television with a remote control
- Ziploc bag full of water
- Black plastic trash bag
- Piece of plastic (like a plastic spoon or cup)
- Metal pot or pan (not Teflon coated)
- Clean piece of white paper
- Two pairs of sunglasses (the polarizing kind rated for UV protection work well)

Light Waves Part 2

- Small box with lid (like a shoe box)
- Tracing paper (1 sheet)
- Microwave
- BIG bar of Hershey's chocolate (any type)
- Water in a shallow glass baking dish
- Mirror (like a hand mirror from the bathroom)
- Long-wave UV lamp
- 2 yardsticks (AKA meterstick)
- 10-20 popsicle sticks
- Index cards or pieces of cardboard
- Set of lenses with extra double-convex lenses (this is the kind in a hand-held magnifying

glass). Pick one of these to get as an extra, or get all 4: 50mm, 150mm, 300mm, 500mm) …OR… instead of buying lenses, simply use eyeglasses and magnifiers that you already have around the house.

- *Optional:* if you want to make the Newtonian telescope, then pick up a concave mirror AND a small mirror (like a mosiac mirror from the craft store, or mirror from a compact).
- Diffraction grating (you can use an old CD in a pinch)
- Sheet of mylar (5" x 8" or larger) and cardboard OR use three rectangular mirrors approx. 8" x 1"
- Scissors, tape
- *Optional:* wooden clothespins (about 4)
- *Optional:* red, green, and blue colored light sticks (Make sure the light inside the red stick really glows RED, not the usual green liquid enclosed in a red-colored tube.)
- *For the last few items on this list, you can select from either group:*

  Group A: Three flashlights, three colors of nail polish (red, green, and blue), clear tape (or plastic wrap) OR…

  Group B: Three 'party bulb' lights (green, blue, and red colored incandescent light bulbs) in clip-on lamps.

Lasers

- Red laser pointer (NOT GREEN!)
- Small mirrors (mosaic mirrors are cheapest)
- 3 large paper clips
- 3 brass fasteners
- 5 index cards
- 2 pins
- 2 razor blades
- 4 clothespins
- Scissors, tape
- White wall (or white paper stuck to the wall)
- PLUS materials from Light Waves 1 & 2

For Grades 9-12:

Laser Light Show

- Red laser pointer (RS #63-1064)
- 2 3VDC motors (RS #273-223)
- 2 gears** or corks (you'll need a solid way to attach the mirror to the motor shaft tip)
- 2 1" round mirrors (use mosaic mirrors)
- 2 DPDT switches with center off (RS #275-1533)
- 20 alligator clip leads (RS #278-1157) OR insulated wire if you already know how to solder
- 2 AA battery packs with 4 AA's (RS #270-408)

- 2 1K or 5K-ohm potentiometers (RS #271-1714)
- Zip-tie (from the hardware store)
- ½ ″ or ¾ ″ metal conduit hangers (size to fit your motors from the hardware store)
- 3 sets of ¼ ″ x 2″ bolts, nuts, and washers
- 1 tupperware container (at least 7″ x 5″) with lid
- Basic tools (scissors, hot glue gun, drill, wire strippers, pliers, screwdriver)

**If you have trouble finding these parts (with the ** next to them), just send us an email.

Laser Communicator

This project requires soldering. We'll teach you how to solder, but you need a soldering iron. If you don't have a soldering iron, save this project for another time.

- Red laser pointer
- 220-ohm resistor (RS #271-1313)
- 8-ohm audio transformer (RS #273-1380)
- 9V battery clip (RS #270-325) & 9V battery
- CdS cell (RS #276-1657)
- SPST push-button switch (RS #275-646) or similar
- Audio plug (RS #274-287) – save the second one in the package for Unit 11
- Bi-polar LED (RS #276-012)
- 2 AA battery packs with 3 AA's (RS #270-408)
- Crystal earphone (Part: '*EAR1*' from www.crystalradiosupply.com) OR get a Mini Audio Amplifier (RS #277-1008) *Note: If you're ordering a ceramic earphone, get at least three for later projects in Alternative Energy.*
- Tools (scissors, hot glue gun, wire strippers, pliers, soldering iron with stand, solder)

Key Vocabulary

The three primary **colors of light** are red, blue, and green. Red and green light mixed together make yellow light. Prisms unmix light into its colors (wavelengths).

Concave lenses work to make objects smaller (door peep hole), and are curved inward like a cave.

Convex lenses make them larger (magnifying lenses), and have a 'bump' in the middle you can feel with your fingers.

The amount of **energy** a photon has determines whether it's a particle or a wave. Photons with the lowest amounts of energy and longest wavelengths (some are the size of football fields) are **radio waves**. The next step up are **microwaves,** which have more energy than radio waves. **IR** has slightly more energy, and **visible light** (the rainbow you can see with your eyes) has more energy and shorter wavelengths. Ultraviolet (UV) light has more energy than visible, and x-rays have even more energy than **UV**, and finally the deadly **gamma rays** have the most amount of energy.

Filters can be used to block certain wavelengths.

Intensity, or brightness, is the amount of photons (packets of light) you have in a certain amount of space. A flashlight has less intensity than a car headlight.

LASER stands for Light Amplification by Stimulated Emission of Radiation. Most lasers are monochromatic (one color). Lasers are concentrated beams of light, and are illuminated by small particles (like smoke and dust).

Lenses work to bend light in a certain direction (refraction). A lens is a curved piece of glass or plastic that changes the speed of the light. Lenses have the same effect on lasers as on light beams.

Light can be defined by four things: intensity (how bright), frequency (or wavelength), polarization (the direction of the electric field), and phase (time shift).

Objects can either be a **light source** (like the sun) or **reflect light** (like the moon).

Light can change speeds, but the maximum **light speed** is through a vacuum (186,000 miles per second). Light changes speeds when it passes through a different material (like water, glass, or fog).

Depending on the **optical density** of the material, light will bend by different amounts. Glass is optically denser than water. Water is more optically dense than air.

When two beams of light are out of phase with each other, it's like playing a *G* and *A* on the piano. This is called **phase shift**.

Blue and UV light eject electrons from metal plates, but red light does not (**photoelectric** effect).

Polarization has to do with the direction of the electric field. Your sunglasses are polarizing filters, meaning that they only let light of a certain direction in.

When a beam of light hits a window, it bends and changes speed (**refraction**). Technically, the wavelength (color) changes but the frequency stays the same. In order for this to happen, the speed of light must also change.

Razor-edge **slits** create interference patterns. Slits are skinny holes that allow light to pass through. Scientists use slits to filter out all other light sources except the one they want to use in their experiment.

When you change the **wavelength**, you change the color of the light. The wavelength (λ) equals the speed of light (c) divided by the frequency (ν), or $\lambda = c / \nu$.

Unit Description

Energy can take one of two forms: matter and light (called electromagnetic radiation). Light is energy in the form of either a particle or a wave that can travel through space and some kinds of matter.

Low electromagnetic radiation (called radio waves) can have wavelengths longer than a football field, while high energy gamma rays can destroy living tissue. We're going to have a look at the nutty fellow called the 'photon' and its very odd behavior during two important experiments that, at first glance, seem to be in conflict with each other. The behavior of light is so strange that scientists are still trying to work out the details.

Objectives

Lesson 1: Light Waves

We're going to take a deep look at the nature of light and its behavior during different types of experiments to try to figure out its properties.

Light can travel through the vacuum of space as well as solid substances like glass.

Energy exists as either matter or electromagnetic radiation.

Scientist are still trying to make heads or tails of this thing called light, and near as they can tell, it sometimes interacts like a particle (like a marble) and other like a wave (like on the ocean), and you really can't separate the two because they actually complement each other.

Highlights for this lesson:

- Light can travel through a vacuum, like space.
- Light can change speeds, but the maximum speed is through a vacuum (186,000 miles per second).
- Low frequency electromagnetic waves are called radio waves, which are *not* the same as sound waves.
- Light you can see (visible light like a rainbow) makes up only a tiny bit of the entire electromagnetic spectrum.
- Light has wavelength (frequency, or color), intensity (brightness), polarization (direction), and phase (time shift).
- The three primary colors of light are red, blue, and green. Red and green light mixed together make yellow light.
- Prisms unmix light into its colors (wavelengths).
- Light changes speeds when it passes through a different material (like water, glass, or fog).
- Lenses work to bend light in a certain direction (refraction).
- Concave lenses work to make objects smaller (door peep hole), convex lenses make them larger (magnifying lenses).

Objectives

Lesson 2: Lasers

Lasers are super-cool gadgets that focus the light energy into a narrow beam you can tease cats and small kids with. Lasers first made their appearance in the 1960s, but had been thought about since the early 1900s by Einstein. We’re going to learn how to split, shatter, mix, bounce, gyrate, and spray laser light beams across our homemade lab bench.

Highlights for this lesson:

- LASER stands for Light Amplification by Stimulated Emission of Radiation.
- Most lasers are monochromatic (one color).
- Filters can be used to block certain wavelengths.
- Razor-edge slits create interference patterns.
- Laser beams are illuminated by small particles in the air (like dust or fog).
- Lenses have the same effect on lasers as on light beams.
- Lasers are concentrated beams of light.
- When a laser is aimed at a window, part of the beam passes through while the rest is reflected back.
- Aiming a laser on a spinning mirror changes the position of the laser beam reflection.

Textbook Reading

Imagine tossing a rock into a still pond and watching the circles of ripples form and spread out into rings. Now look at the ripples in the water… notice how they spread out. What makes the ripples move outward is *energy*, and there are different kinds of energy, such as electrical (like the stuff from your wall socket), mechanical (a bicycle), chemical (a campfire) and others.

The ripples are like light. Notice the waves are not really moving the water from one side of the pond to the other, but rather move energy across the surface of the water. To put it another way, energy travels across the pond in a wave. Light works the same way – light travels as energy waves. Only light doesn't need water to travel through the way the water waves do - it can travel through a vacuum (like outer space).

Light Reflection or Source?

A candle is a light source. So is a campfire, a light bulb, and the sun. An apple, however, reflects light. It doesn't give off any light on its own but you can see it because light waves bounce off the apple into your eye. If you shut off the light, then you can't see the apple. In this same way, the sun is a light source, and the moon is a light reflector.

The Speed of Light

Light can change speed the same way sound vibrations change speed. (Think of how your voice changes when you inhale helium and then try to talk.)

The "speed limit" of light is 186,000 miles per second – that's fast enough to circle the Earth seven times every second, but that's also inside a vacuum.

You can get light going slower by aiming it through different substances. In fact, you can get high-energy particles to travel *faster* than light through water. When this happens you get something equivalent to a sonic boom for light (called Cherenkov Radiation) which emits a cone of blue light.

In our own atmosphere, light travels slower than it does in space.

How do I study light?

Most light we can't see with our eyes, and that makes it hard to study.

If you place your hand above (carefully!) a burner on an electric stove as it heats up, you can detect the light coming from the stove long before it starts to glow red. You are detecting the infrared light using your skin.

After a day at the beach, your sunburn is the result of absorbing UV light.

How do I detect light?

Your eyeballs are photon detectors. These photons move at the speed of light and can have all different wavelengths, which correspond to the colors we see. Red light has a longer wavelength (lower energy and lower frequency) that blue light.

If you have a low-energy photon, you might perceive it as a radio wave by turning on your radio in the car and 'seeing' what signals you can pick up.

Are radio waves *sound* waves?

Radio waves are *not* the same thing as sound waves. Radio waves are low-energy *light* waves. Think about this: you can't hear the stuff coming off a radio station antenna – you need a way to transform the light waves into sound waves (which is exactly what your radio does). The sounds from a scream are vibrating air molecules, while radio waves are actually light beams moving much, *much* faster.

How does a microwave work?

Your microwave heats your dinner by aiming very specific light beams at your food. The light beams excite the water molecule (which is present is nearly all foods), and this energy makes the water molecules jiggling around faster (called *heat*). The energy from the light gets pumped into your food. Which is why you never want to run a microwave without food inside, as it will 'cook itself' and blow up.

What's 'infrared'?

When you press the button on your remote control to your TV, you're using infrared light (IR) to control your TV. Infrared light has a bit more energy that microwave light, but it's still invisible to our eyes.

However, snakes can detect IR and see the redder hues that we can't. Every warm body gives off light in the IR, so snakes use this to find mice in the cool night.

Why can't I see most kinds of light?

Different detectors are sensitive to different colors. Your eyeballs are sensitive to specific colors in the 400-700 nm (nanometer) range (which is how long one wavelength is. A nanometer is extremely tiny!

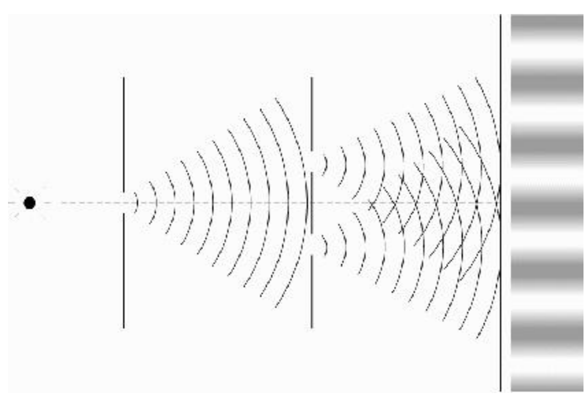
The frequency of red light is around 430 trillion Hz (Hertz, which is one wave cycle per second). If you were to count the number of waves passing a certain point in one second, you'd count 430 trillion waves. If you counted 750 trillion waves, the light would be violet. Different colors have different frequencies.

What are all the different kinds of light?

Photons with the lowest amounts of energy and longest wavelengths (some are the size of football fields) are **radio waves**. The next step up are **microwaves,** which have more energy than radio waves. **IR** has slightly more energy, and **visible light** (the rainbow you can see with your eyes) has more energy and shorter wavelengths. Ultraviolet (UV) light has more energy than visible, and x-rays have even more energy than **UV**, and finally the deadly **gamma rays** have the most amount of energy.

A Brief History of light

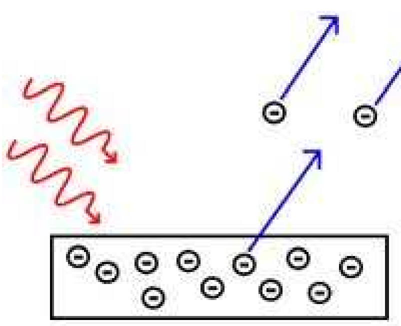
In the early 1800s, Thomas Young's double-slit experiment showed the world that light was a wave.



He aimed sunlight through two very narrow slits and found a wave-like interference pattern on the wall behind the slits, something you'd only get with waves.

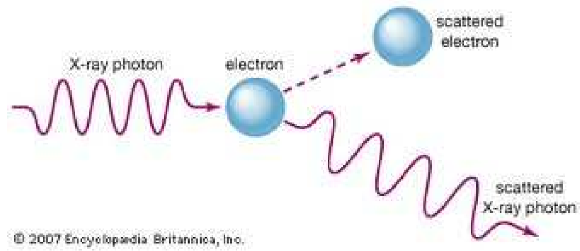
James Maxwell predicted light would be an electromagnetic wave (more on this in Unit 10) in the 1860s after doing several experiments with electricity and magnetism. He further predicted that this wave would travel at speed *c* (where *c* = 186,000 miles per second).

In the 1800s, scientists had observed the photoelectric effect, in which a light particle hits a free electron and knocks it out of a metal plate. No wave could do this so it baffled scientists for a long time. (More on this effect later.)



In 1905, Einstein explained the photoelectric effect by suggesting that light comes in bundles and behaves like it was a particle.

The *Compton Effect* in 1923 showed what happens when x-rays interact with electrons: the x-ray hits an electron (something a wave could not do), gets deflected (changes direction) while also transferring some of its energy to the electron.



So we have two seemingly opposing points of view – light sometimes acts like a wave, and sometimes acts like a particle. So which is it?

It turns out to be both. Light is both a particle and wave, and furthermore, these two ideas actually complement each other.

Light Comes in Packets

It is important to know that light is said to be 'quantized'. You could say that M&M's are quantized – they are little packets of a certain amount of chocolate.

Light comes in packets called photons. This idea seems a bit strange, because most of your everyday experience with light is when it acts like a wave.

If you try to detect light, it behaves like particles (by the photoelectric experiment, the Compton effect, or even on your video camera pixels).

If you don't try to detect light, it acts like a wave and has wave interference patterns. You're on the larger scale when you don't try to detect the individual packets of light, so you don't notice that light is quantized.

It would be like trying to go the store and buying 2 tablespoons of eggs. They just don't come packaged that way. There's a minimum set package for the amount egg you need in a recipe. That's like trying to detect a photon.

However, if you're making 2 million cookies, you'd order eggs by the truckload and no longer worry about if you had exactly the right amount down to the single egg – you'd say "give me 25 pounds of eggs" or something similar. That's when light acts like a wave – it's more of a continuous effect.

Usually, the amount of energy a photon has determines whether it's a particle or a wave. Lower energy photons (like radio and microwave) travel like waves, and higher energy gamma rays interact like particles.

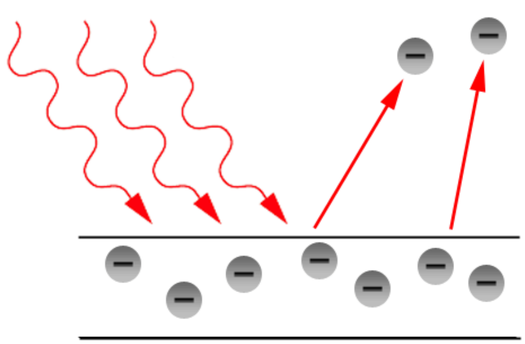
In most cases, light behaves like a wave – a disturbance moving energy from one spot to another. You can measure its wavelength (the distance between two peaks) and frequency (the number of peaks passing a point each second). I'll show you how to do this with the experiments in this unit.

When we think of light as tiny packets ('quanta' of energy) called photons, then we're talking about light acting like a particle. Photons carry no mass, but a fixed amount of energy. The energy depends on the wavelength. For example, blue light (shorter-wavelength photons) has more energy than red light (longer-wavelength photons).

Einstein received a Nobel Prize for figuring out what happens when you shine blue light on a sheet of metal. When he aimed a blue light on a metal plate, electrons shot off the surface. (Metals have electrons which are free to move around, which is why metals are electrically conductive. More on this in Unit 10).

When Einstein aimed a red light at the metal sheet, nothing happened. Even when he cranked the intensity (brightness) of the red light, still nothing happened. So it was the energy of the light (wavelength), not the number of photons (intensity) that made the electrons eject from the plate. This is called the 'photoelectric effect'. Can you imagine what happens if we aim a UV light (which has even more energy than blue light) at the plate?

This photoelectric effect is used by all sorts of things today, including solar cells, electronic components, older types of television screens, video camera detectors, and night-vision goggles.



This photoelectric effect also causes the outer shell of orbiting spacecraft to develop an electric charge, which can wreck havoc on its internal computer systems.

A surprising find was back in the 1960s, when scientists discovered that moon dust levitated through the photoelectric effect. Sunlight hit the lunar dust, which became (slightly) electrically charged, and the dust would then lift up off the surface in thin, thread-like fountains of particles up ¾ of a mile high.

So what *is* light?

There is no contradiction between light acting like a particle or a wave. You need both to describe all the ways that light behaves. Note that you can't have both at the same time, however.

What ultimately decides which light decides to do? You.

If you do an experiment that involves wave aspects of light, like shining a laser through slits, you'll see an interference pattern. If you set up an experiment that detects light as a particle, like the photoelectric effect, you'll find that light acts like a particle.

Does this seem absurd to you? If it does, you're not alone. Most scientists feel the same way!

Nevertheless, it's the way the universe is wired.

How does light behave?

Light which can be defined by four things: intensity (how bright), frequency (or wavelength), polarization (the direction of the electric field), and phase (time shift).

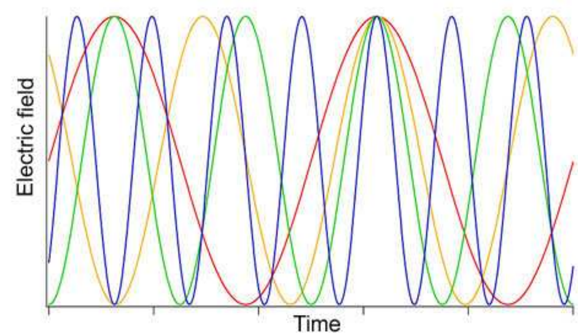
Let's take a look at each one of these things in detail:

What is wavelength and frequency?

The electromagnetic spectrum shows the different energies of light and how the energy relates to different frequencies. In 'math-speak', the wavelength (λ) equals the speed of light (c) divided by the frequency (ν), or
$\boldsymbol{\lambda = c / \nu}$.

The speed of light is: $c = 3 \times 10^8$ m/s (300,000,000 meters per second).

You and I don't detect most electromagnetic waves. Our eyeballs can only 'see' in the 400-700 nm (nanometer) range, which is only a small part of the entire spectrum, so we need special detectors to find the rest of the photons zipping around.



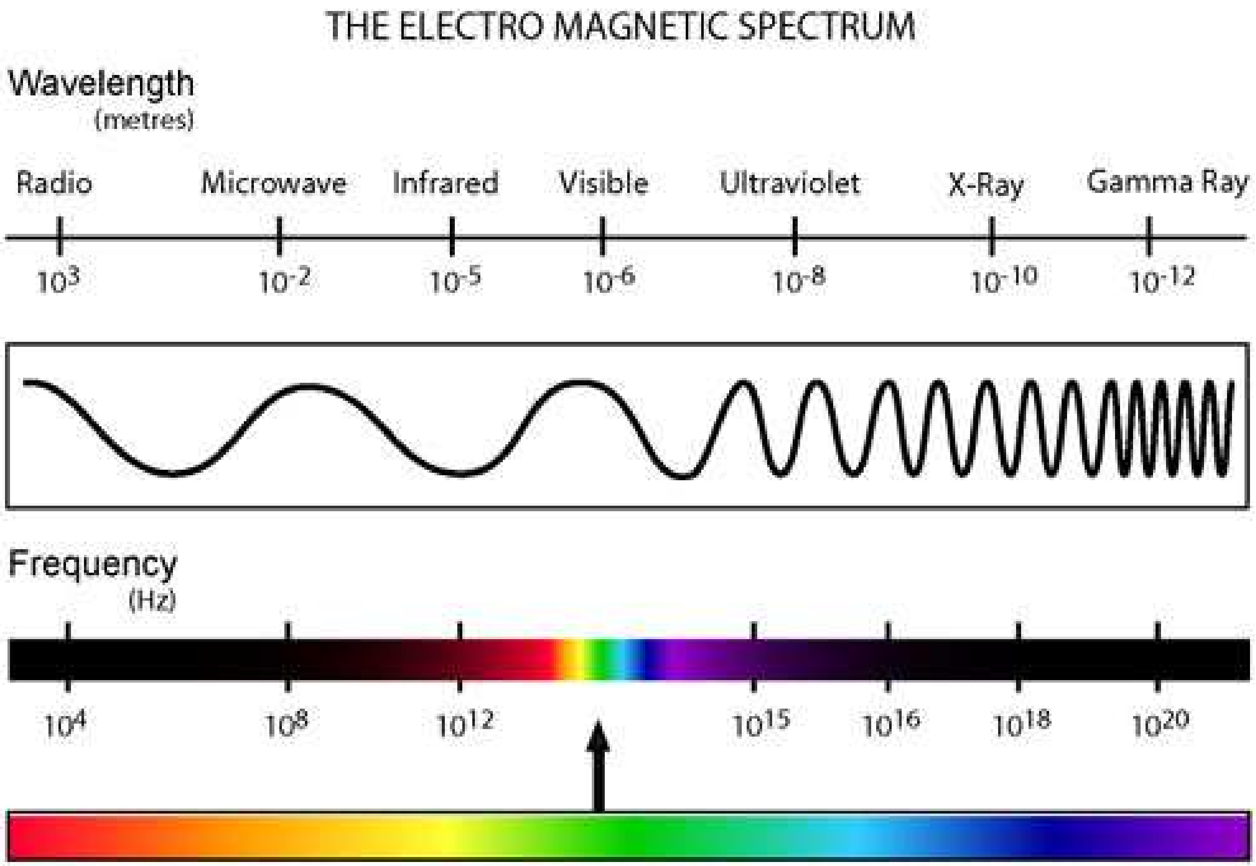
Radio signals are picked up using an antenna (similar to your satellite dish in the backyard).

X-rays are more difficult to detect, because they would rather go through the detector than bounce off of it, so we use complicated mathematics and the shadows of the photons to "see" x-rays.

Gamma rays are the toughest to detect – they are very highly energized packets of light that would rather zoom through mirrors than be detected.

What about colors?

Do you see where the "visible light" rainbow section is in the electromagnetic spectrum image on the next page? This small area shows the light that you can actually see with your eyeballs.



Note that the "rainbow of colors" that make up our entire visible world only make up a small part of all the light zooming around the countryside. So where do different colors come from?

When you change the wavelength, you change the color of the light. If you pass a beam white light through a glass filled with water that's been dyed red, you've now got red light coming out the other side. The glass of red water is your filter. But what happens when you try to mix the different colors together?

Imagine you're a painter. What three colors do you need to make up any color in the universe? (You should be thinking: red, yellow, and blue.)

Here's a trick question - can you make the color "yellow" with only red, green, and blue as your color palette? If you're a scientist, it's not a problem. But if you're an artist, you're in trouble already.

The key is that we would be mixing light, not paint. Mixing the three primary colors of light gives white light. If you took three light bulbs (red, green, and blue) and shined them on the ceiling, you'd see white. And if you could magically un-mix the white colors, you'd get the rainbow (which is exactly what prisms do.)

If you're thinking yellow should be a primary color - it *is* a primary color, but only in the artist's world. Yellow *paint* is a primary color for painters, but yellow *light* is actually made from red and green light.

(Easy way to remember this: think of Christmas colors – red and green merge to make the yellow star on top of the tree.)

Polarization

To understand polarization, we have to have a deeper look into what light really is. Have you wondered by scientists call light *electromagnetic radiation*? What does electricity and magnetism have to do with light?

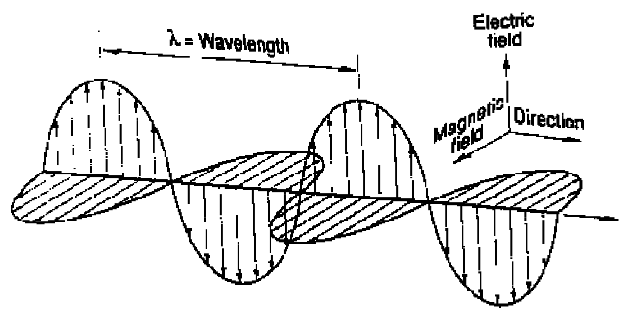
Energy in the form of electromagnetic (EM) radiation is one of the two forms of energy in the universe (matter being the other). This type of energy is made when electrically charged particles (like electrons) move.

One of the most important discoveries in science was that electricity and magnetism are linked. (We'll be going into much more detail later on in Units 10 and 11.)

A moving electrical charge creates a magnetic field. Moving charges (electric fields) create magnetic fields.

Also - moving magnetic fields create electric fields. If you wrap a nail with wire and rub a magnet vigorously along its length, you can measure a voltage. (We'll do more on this in our unit on Electricity and Magnetism.)

So a moving electrical charge creates a magnetic field, and the creation of the magnetic field creates an electric field, which then creates a magnetic field, which in turn created as electric field… and soon you have a wave leapfrogging through space just like a wave on the ocean. That wave is light. The kind of light wave you have (radio, visible, x-ray) depends on how much energy your wave has.



Polarization has to do with the direction of the electric field. Your sunglasses are polarizing filters, meaning that they only let light of a certain direction in. The view through the sunglasses is a bit dimmer.

Polarizing sunglasses also reduce darken the sky, which gives you more contrast between light and dark, sharpening the images.

Photographers use polarizing filters to cut out glaring reflections. The image on the right was taken without a polarizer on the camera. See the glare?

Intensity of Light

You can easily figure out that a car headlight has a higher intensity than a flashlight, because it's brighter. But what if the headlight was 100 miles away? Does the intensity change?

Astronomers use this idea when looking at the stars. Just because a star *appears* brighter doesn't mean it's more luminous. The distance to the star also comes into play when figuring out stellar brightness (which relates directly to the star's temperature).

Think of intensity as the amount of light over a certain amount of area. The amount of sunlight that falls on Venus is greater than for the Earth, as Venus is closer to the sun.

The intensity decreases as you move further away from the sun (but it decreases at a rate proportional to the distance *squared*). If we placed Earth way out where Pluto is, then the amount of light energy that reaches the distant Earth would be much, much less.

Phase of Light

When you play the musical note **A** on a piano, you have eight different choices. The **A** on the low end is also an **A** on the higher octaves. Why is that?

The **A** notes are *harmonics* of each other, meaning that they are sound waves shifted by a very specific amount.

Light energy does the same thing, only it's called a *phase shift*. When two beams of light are out of phase with each other, it's like playing a **G** and **A** on the piano. But when they are in phase, it's like playing two different **A** notes.

The time zones on the Earth are an example of phase differences. When it's 9am in California, it is noon in New York. Even though the moment in time is the same, the clock on the wall tells you the phase shift is three hours.

Depending on the phases of light, they will interact in different patterns.

What's Refraction?

When light hits a different substance (like a window pane), the wavelength changes, but the frequency stays the same. In order for this to happen, the speed of light must also change. (Sound does this, too!)

In some cases, the change of wavelength turns into a change in the direction of the beam.

For example, if you stick a pencil is a glass of water and look through the side of the glass, you'll notice that the pencil appears shifted. The speed of light is slower in the water (140,000 miles per second) than in the air (186,000 miles per second), called optical density, and the result is bent light beams and broken pencils.

You'll notice that the pencil doesn't always appear broken. Depending on where your eyeballs are, you can see an intact *or* broken pencil. This is a very point about refraction: when light enters a new substance (like going from air to water) perpendicular to the surface (looking straight on), refractions does not occur.

However, if you look at the glass at an angle, then depending on your sight angle, you'll see a different amount of shift in the pencil. Where do you need to look to see the greatest shift in the two halves of the pencil? (Hint: move the pencil back and forth slowly.)

There is another important idea about refraction we need to figure out: depending on if the light is going from a lighter to an optically denser material (or vice versa), it will bend different amounts. Glass is optically denser than water, which is denser than air. Here's a chart:

Vacuum	1.0000
Air	1.0003
Ice	1.3100
Water	1.3333
Ethyl Alcohol	1.3600
Pyrex	1.4740
Karo Syrup	1.4740
Vegetable Oil	1.4740

Plexiglas	1.5100
Diamond	2.4170

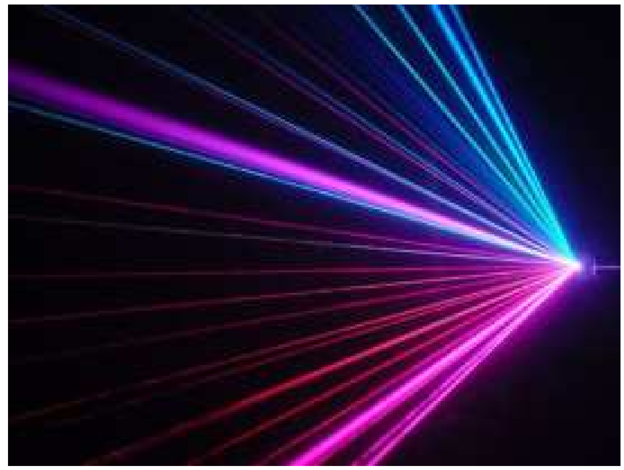
This means if you place a Pyrex container inside a beaker of vegetable oil or Karo syrup, it will disappear (this also works for some mineral oils). Note however that the optical densities of liquids vary with temperature and concentration, and manufacturers are not perfectly consistent when they whip up a batch of this stuff, so some adjustments are needed.

Not only can you change the shape of objects by bending light (broken or whole), but you can also change the size. Magnifying lenses, telescopes, and microscopes use this idea to make objects appear different sizes.

Lasers

The word "LASER" stands for Light Amplification by Stimulated Emission of Radiation. A laser is an optical light source that emits a concentrated beam of visible light. Lasers are usually monochromatic – the light that shoots out is usually one wavelength and color, and is in a narrow beam.

By contrast, light from a regular incandescent light bulb covers the entire spectrum as well as scatters all over the room. (Which is good, because could you light up a room with a narrow beam of light?)



A laser is a high-energy, highly-focused beam of light.

How Does a Laser Work?

Think of small kids on sugar. When you add energy to these atoms (giving sugar to the kids), they really get excited and bounce all over the place. When the atoms relax back down to their "normal" state, they emit a photon (a light particle). Think of the kids as they are coming down from their sugar high, all collapsed on the couch, a lot less energetic than they were a minute ago.

A laser controls the way energized atoms release photons. Imagine giving only half of the kids sugar cookies, and picture how they would bounce all over the place. You'd have half of the kids having very high-energy levels, while the other half would be sitting down in a lower energy state. The sugar-kids' energy is infectious, though, and pretty soon, the rest of the kids are joining in and sharing in their excited energy. This is how a laser "charges" the atoms inside the gas medium – by only energizing half the atoms, and allowing the other half to get excited just by being near the first half.

Imagine those sugar kids zooming all over the playground, a mixture of joy and chaos. Light from an incandescent light bulb works the same way – the bulb emits high energy photons that bounce all over the place. Can you round up the kids and get them to jumping in unison? Sure you can – just hit the play button on a song, and they'll be clapping and stamping together. You can do the same with light – when you focus the energy into a narrow beam, it's much more powerful than having it scattered all over the place. That's just what a laser is – a high-energy, highly-focused beam of light.

Laser Safety

Before we start our laser experiments, you'll need eye protection – tinted UV ski goggles are great to use, as are large-framed sunglasses, but understand that these methods of eye protection will not protect your eyes from a direct beam. They are intended as a general safety precaution against laser beam scatter.

Activities, Experiments, Projects

Lesson 1: Light Waves

Note: This section is an abbreviated overview of the experiments online.

Experiment: Pinhole Camera

This is the simplest form of camera – no film, no batteries, and no moving parts that can break. The biggest problem with this camera is that the inlet hole is so tiny that it lets in such a small amount of light and makes a faint image. If you make the hole larger, you get a brighter image, but it's much less focused. The more light rays coming through, the more they spread out the image out more and create a fuzzier picture. You'll need to play with the size of the hole to get the best image.

While you can go crazy and take actual photos with this camera by sticking on a piece of undeveloped black and white film (use a moderately fast ASA rating), I recommend using tracing paper and a set of eyeballs to view your images. Here's what you need to do:

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1. Use a cardboard box that is light-proof (no leaks of light anywhere).

2. Seal light leaks with tape if you have to. Cut off one side of the box (Note – there's no need to do this if you're using a shoebox).

3. Tape a piece of tracing paper over the cutout side, keeping it taut and smooth.

4. Make a pinhole in the box side opposite of the tracing paper.

5. Point the pinhole at a window and move toward or away from the window until you see its image in clear focus on the tracing paper.

OPTIONAL: You can hold up a magnifying glass in front of the pinhole to sharpen the image.

Experiment: Light Tricks

When light rays strikes a surface, part of the beam passes through the surface and the rest reflects back, like a ball bouncing on the ground. Where it bounces depends on how you throw the ball.

Have you ever looked into a pool of clear, still water and seen your own face? The surface of the water acts like a mirror and you can see your reflection. (In fact, before mirrors were invented, this was the only way people had to look at themselves.) If you were swimming below the surface, you'd still see your own face – the mirror effect works both ways.

Have you ever broken a pencil by sticking it into a glass of water? The pencil isn't really broken, but it sure looks like it! What's going on?

When a beam of light hits a different substance (like the water), the wavelength changes because the speed of the light changes. If you're thinking that the speed of light is always constant, you're right… in a vacuum like outer space between two reference frames.

But here on Earth, we can change the speed of light just by shining a light beam through different materials, like water, ice, blue sunglasses, smoke, fog, even our own atmosphere. How much the light speed slows down depends on what the material is made of. Mineral oil and window glass will slow light down more than water, but not as much as diamonds do.

How broken the pencil appears also depends on where you look. In some cases, you'll see a perfectly intact pencil. Other times, you'll guess neither piece is touching. This is why not everyone can see a rainbow after it rains. The sun *must* be at a low angle in the sky, and also behind you for a rainbow to appear. Most times, you aren't at the right spot to see the entire arc touch the ground at both ends, either.

Lenses work to bend light the way you want them to. The simplest lenses are actually prisms. Prisms unmix light into its different wavelengths. When light hits the prism, most of it passes through (a bit does reflect back) and changes speed. Since the sunlight is made up of many different wavelengths (colors), each color gets bent by different amounts, and you see a rainbow out the other side.

1. Toss one coin into a water glass (pickle jars work great) and fill with an inch of water. Hold the glass up and find where you need to look to see TWO coins. Are the coins both the same size? Which one is the original coin? (Answer at the bottom of this page.)

2. Look through the top of the glass – how many coins are there now? What about when you look from the side?

3. Toss in a second coin – now how many are there?

4. Remove the coins turn out the lights. Shine a flashlight beam through the glass onto a nearby wall. (Hint – if this doesn't work, try using a square clear container.) Stick a piece of paper on the wall where your light beam is and outline the beam with a pencil.

5. Shine the light at an angle up through the water so that it bounces off the surface of the water from underneath. Trace your new outline and compare… are they both the same shape?

6. Add a teaspoon of milk and stir gently. (No milk? Try sprinkling in a bit of white flour.) Now shine your flashlight through the container as you did in steps 4 and 5 and notice how the beam looks.

7. Use a round container instead of square… what's the difference?

Answers:
1. The smaller coin is the reflection.
2. One coin when glanced from above, two from the side.
3. Four.
4. Beam is a circle.
5. Beam is an oval.
6. I can see the beam through the water!!
7. The round container distorts the beam, and the square container keeps the light beam straight. Both are fun!

Activities, Experiments, Projects

Lesson 2: Lasers

Note: This section is an abbreviated overview of the experiments online.

Experiment: Laser Basics

Before we start building our laser projects, just play with it first. Turn off the lights at night and take your laser on a hunt around the house to see what happens when you shine it on or through different things. Here are some ideas to try:

1. **Shatter the Beam:** Shine your beam over the surface of an old CD. Does it work better with a scratched or smoother surface? You should see between 5-13 reflections off the surface of the CD, depending on where you shine it and how well the "seeing" conditions are.

2. **Beam Scatter:** Pass the laser beam through several cut-crystal objects such as wine glasses or clear glass vases. Is there a difference between clear plastic or glass, smooth or multi-faceted? Try an ice cube, both frosted and wet (clear).

3. **Split the Beam:** Shine the laser beam through a flat piece of glass, such as a window. Can you find the pass-through beam as well as a reflected beam? Windows and clear plastic containers will split your beam in two.

What's going on? When you shine your laser beam through glass (like a window) or plastic (like a soda bottle filled with water and a tiny bit of cornstarch), it splits into two beams – one that passes through, and the other that internally reflects back. You can see these reflections in a darkened fog-filled room.

4. **Colored Filters:** Paint a piece of cellophane or stiff clear plastic with nail polish (or use colored filers) to put in the laser beam.

5. **Diffraction Grating:** You can make a quick diffraction grating by using a feather in the beam.

6. **Polarization:** If you have polarizer filters, use two. You can substitute two pairs of sunglasses. Just make sure they are polarized lenses (most UV sunglasses are). Place both lenses in the beam and rotate one 90 degrees. The lenses

should block the light completely in one configuration and allow it to pass-through the other way.

Why does this happen? Polarization is a way of filtering light. Try this: in a shallow pan filled with water, make a few waves and notice how they travel from one side of the pan to the other. Now add a plastic comb, and notice how the waves stop when they hit the comb – not many pass through to the other side (watch out for the waves that creep around the edges – we're focusing on the pass-through waves only). The comb are the sunglasses, and the water waves are the light waves.

Add a second comb at 90 degrees from the first (as you did with the sunglasses) so it resembles a mesh screen, and notice now how NONE of the waves make it through the comb array. Polarization can filter out various amounts of light, depending on the angle the combs make with each other (90 degrees apart equals total block-out).

7. **Light Bulbs:** In the dark, aim your laser at a frosted incandescent light bulb. The bulb will glow and have several internal reflections! What other types of light bulbs work well?

Did you know that the word LASER stands for Light Amplification by Stimulated Emission of Radiation? And that a MASER is a laser beam with wavelengths in the microwave part of the spectrum? Most lasers fire a monochromatic (one color) narrow, focused beam of light, but more complex lasers emit a broad range of wavelengths at the same time.

In 1917, Einstein figured out the basic principles for the LASER and MASER by building on Max Planck's work on light. It wasn't until 1960, though when the first laser actually emitted light at Hughes Research Lab. Today, there are several different kinds of lasers, including gas lasers, chemical lasers, semiconductor lasers, and solid state lasers. One of the most powerful lasers ever conceived are gamma ray lasers (which can replace hundreds of lasers with only one) and the space-based x-ray lasers (which use the energy from a nuclear explosion) – neither of these have been built yet!

Exercises

Light Wave Exercises

1. Can light change speeds? How about sound waves?
2. Can you see ALL electromagnetic waves with your eyes?
3. Which has a longer wavelength, red or blue light? Which has more energy?
4. Give three examples of a light source.
5. Are radio waves the same thing as sound waves?
6. How does a microwave cook your food?
7. How is a snake like a TV remote?
8. Does UV light have more or less energy than visible light we can see with our eyes?
9. Is light a particle or a wave?

10. What was so cool about Einstein's red light/ blue light experiment?

11. How do you make yellow light? Yellow *paint*?

12. What does a prism do?

13. How far do you need to rotate the sunglasses to block most (if not all) light?

14. Why does the pencil appear bent? Is it always bent?

15. How can you make a glass container disappear?

16. How does a microscope work?

Exercises

Lasers Exercises

1. What does LASER stand for?
2. How is a laser different from an incandescent bulb?
3. What are two things that can split a laser beam?
4. How do you make a laser beam visible?
5. What's the secret behind the laser light show?
6. How do lasers damage things?

Answers to Light Exercises

1. Light can change speed the same way sound vibrations change speed. (Think of how your voice changes when you inhale helium and then try to talk.) The "speed limit" of light is 186,000 miles per second – that's fast enough to circle the Earth seven times every second, but that's also inside a vacuum. You can get light going slower by aiming it through different gases. In our own atmosphere, light travels slower than it does in space.

2. No. Human eyes can only detect a small portion of all light (in the visible range).

3. Red light has a LONGER wavelength and LESS energy than blue light.

4. Campfire, the sun, and a neon OPEN sign.

5. No. Radio waves are LIGHT waves that are very low energy and have a loooooong wavelength.

6. By aiming light beams at your food which are specially tuned to excite the water molecule. Since all foods have water, this works to heat up your food. Excited molecules are ones that jiggle and zip around fast, which is also called *hea*t

7. Both use IR (infrared) light. The snake is a detector and the TV remote is an emitter.

8. Longwave UV are black lights you can get on Halloween that make things glow and fluoresce, and these types of lights are not damaging to living tissue even though they have more energy than visible light. Short wave UV (which have shorter wavelengths and more energy), however, *are* damaging and can burn your skin.

9. Both, and you really can't separate the two.

10. When you aim a blue light on a metal plate, electrons shoot off the surface. Red light doesn't cause electrons to eject, however, no matter how bright you make the red light. It's the wavelength, not the intensity that matters with the photoelectric effect.

11. Mix together green and red light to get yellow light. Yellow paint is a fundamental color that can't be made from any others – you have to start with yellow.

12. A prism un-mixes the light beams into its separate colors.

13. The sunglasses need to be 90 degrees from each other.

14. The pencil appears bent (or broken) because the water and the glass change the speed of light. Depending on where your line of sight is, you can make the pencil appear broken or whole.

15. Besides hiding it in a closet, you can also place a Pyrex glass container inside a glass container filled with mineral oil, vegetable oil, or light Karo syrup. The index of refraction is the same for both, so our eyes are unable to see the difference between the two.

16. A microscope uses lenses that bend the light to make things appear larger. Using two convex lens magnifiers, you can find the tiny owl in the upper corner of the dollar bill that's normally hidden to the naked eye.

Answers to Lasers Exercises

1. Light can change speed The word "LASER" stands for Light Amplification by Stimulated Emission of Radiation.

2. Light from a regular incandescent light bulb covers the entire spectrum as well as scatters all over the room. A laser beam is monochromatic – the light that shoots out is usually one wavelength and color, and is in a narrow beam.

3. Glass (like a window pane) and clear plastic (like a water bottle).

4. Take it in a steamy room, like just after a hot shower. Or aim it through a glass of water that has a drop of milk in it.

5. The laser beam hits a spinning mirror that's off-center. The more angled the mirror mount, the larger the image that the laser traces out. Which is why this is a perfect project for kids – the sloppier they build it, the better the laser light show.

6. High-power CO_2 lasers have an intense amount of heat that melts through metal. These aren't the lasers we're going to be working with! The lasers at the grocery store are Class I lasers, which will harm your eye if you stare into it without blinking once for at least 15 minutes. These 'keychain' lasers are Class II & III, some of which can overpower your retina in less than a minute, and the damage is irreversible. When I work with kids in a live Laser Lab class, I have a zero-tolerance rule (which is explained beforehand): if misused, I just walk over, take the laser without a word, and keep it. Class proceeds as normal, and it's up to the kid to figure out how to finish the project.