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, which has baffled scientists for over a century.

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Key Vocabulary

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

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

Convex lenses make objects appear larger (think of magnifying lenses), and have a 'bump' in the middle that 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 in size is **microwaves,** which have more energy than radio waves. **Infrared (IR) light** 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 is visible, and X-rays have even more energy than **UV**. Finally, the deadly **gamma rays** have the greatest 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 **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Most lasers are monochromatic (one color). Lasers are concentrated beams of light and can be 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 different materials (like water, glass, or fog).

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

When two beams of light are out of phase with each other, it's like playing a *G* and *A* simultaneously 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.

Scientists 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 times it acts like a wave (like on the ocean). You really can't separate the two because they actually complement each other.

Highlights

- Light can travel through a vacuum, like space.
- Light can change speeds, but the maximum speed it can attain is when it travels through a vacuum (186,000 miles per second).
- 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 separate 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 appear smaller (think of a door peep hole), while convex lenses make them appear larger (magnifying lenses).

Objectives

Lesson 2: Lasers

Lasers are super-cool gadgets that focus the light energy into a narrow beam that you can then 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

- LASER stands for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.
- 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, including electrical (like the stuff from your wall socket), mechanical (a bicycle), and chemical (a campfire).

The ripples are like light. Notice that the waves are not really moving the water from one side of the pond to the other, but rather the waves move the 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; however, light doesn't need water to travel through the way the water waves need water. Light can travel through a vacuum (like outer space).

Light Reflection or Source?

A candle is a light source, and 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 only its speed 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?

We can't see most light 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) than 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 molecules (which are present in nearly all foods), making the water molecules jiggle 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—

if you do, 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. IR light has a bit more energy than 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 of the 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!

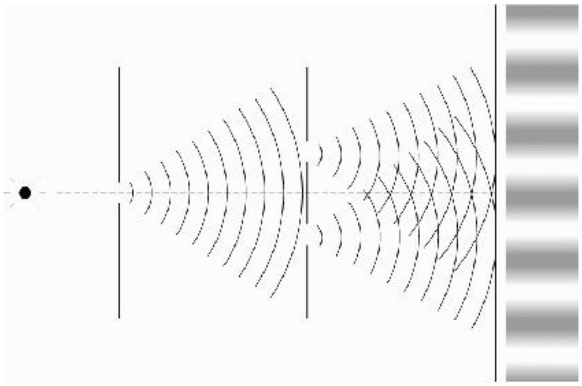
The frequency of red light is around 430 trillion Hz (A Hertz is equal to one wave cycle per second). If you were to count the number of waves passing a certain point in one second, you'd count 430 trillion waves. If you counted 750 trillion waves, the light would be violet. Different colors have different 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 in wave size is **microwaves,** which have more energy than radio waves. **IR light** 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**. Finally the deadly **gamma rays** have the greatest amount of energy.

A Brief History of light

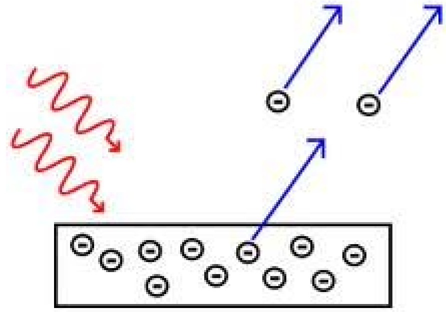
In the early 1800s, Thomas Young's double-slit experiment showed the world that light was a wave.



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

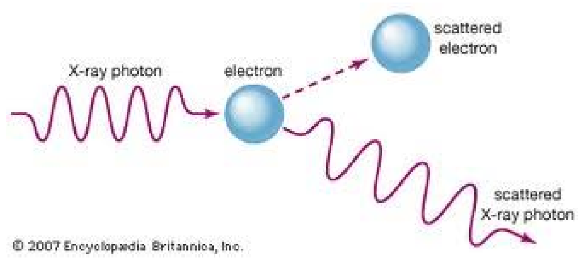
James Maxwell predicted light would be an electromagnetic wave (more on this in Unit 10) in the 1860s after doing several experiments with electricity and magnetism. He further predicted that this wave would travel at speed *c* (where *c* = 186,000 miles per second).

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 a particle.

In 1923, the *Compton Effect* showed what happens when X-rays interact with electrons: the X-ray hits an electron (something a wave could not do) and 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 that light is both a particle and a wave. 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&Ms 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 in most of your everyday experience with light you see it act 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 and it has 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.

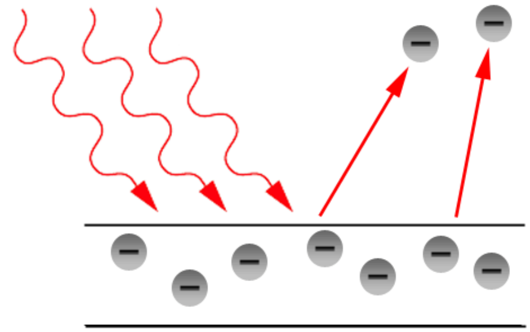
In most cases, light behaves like a wave, or a disturbance moving energy from one spot to another. You can measure its wavelength (the distance between two peaks) and frequency (the number of peaks passing a point each second). I’ll show you how to do this with the experiments in this unit.

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 would happen if we were to 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 to 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 way light decides to behave? 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 can be defined by four things: intensity (how bright), frequency (or wavelength), polarization (the direction of the electric field), and phase (time shift).

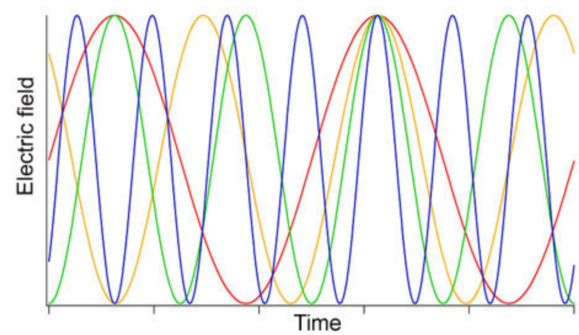
Let's take a look at each one of these things in detail.

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
$\lambda = c / \nu$.

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.

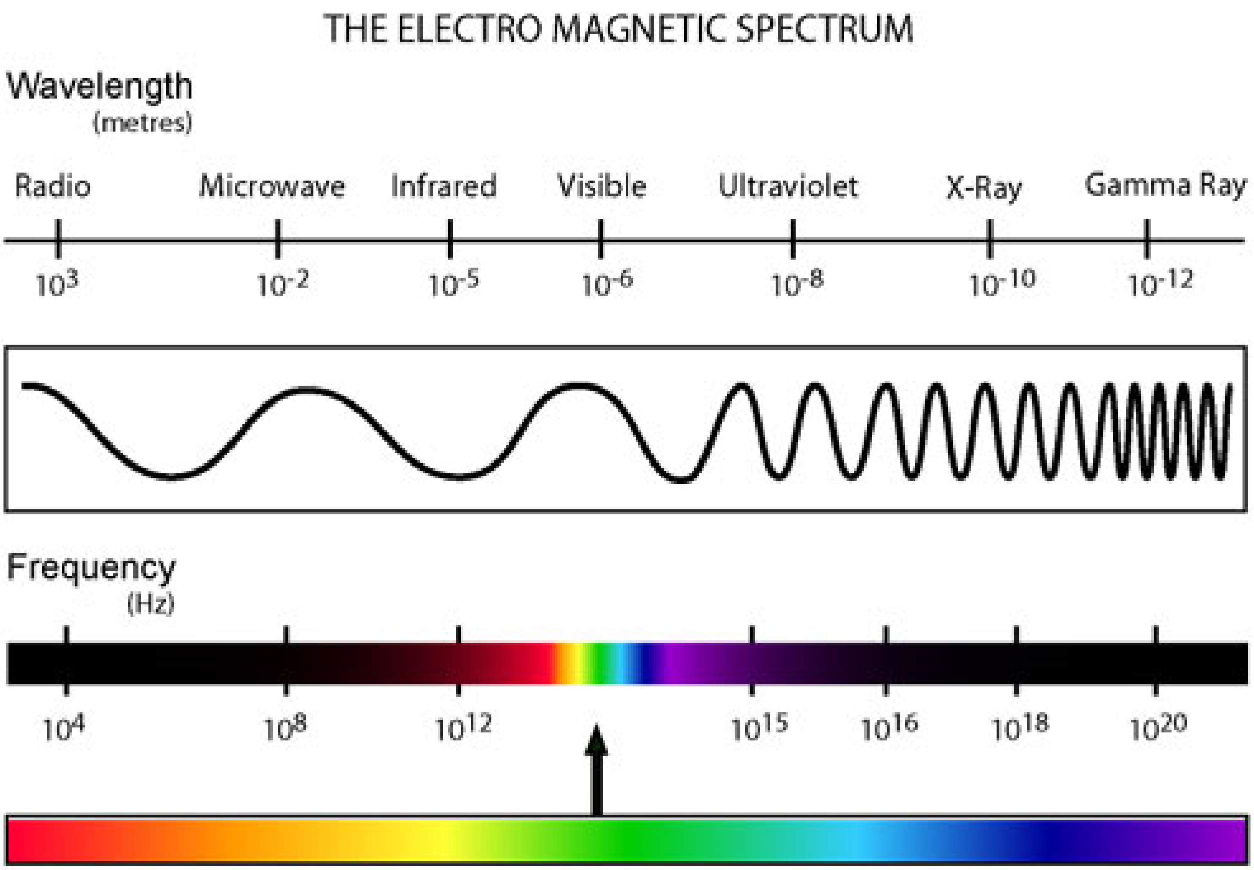
What about colors?

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 of 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. (You should be thinking: red, yellow, and blue… and yes, you are right if you're thinking that the real primary colors are cyan, magenta, and yellow, but some folks still prefer to think of the primary



colors as red-yellow-blue…either way, it’s really not important which primary set you choose.)

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 were to take three light bulbs (red, green, and blue) and shine 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, well, 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.

An easy way to remember this is to 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 ever wondered why scientists call light *electromagnetic radiation*? What do electricity and magnetism have to do with light?

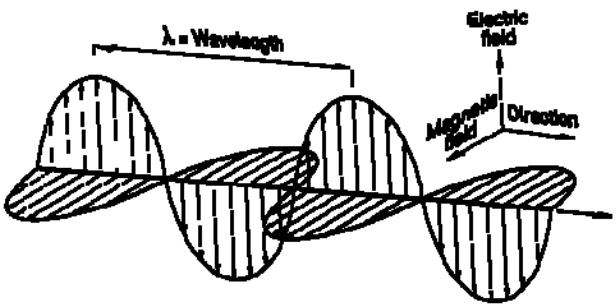
Energy in the form of electromagnetic (EM) radiation is one of the two forms of energy in the universe (matter being the other). This type of energy is made when electrically charged particles (like electrons) move.

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 creates an 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 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 that which falls on 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 would reach 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 at the same time. But when they are in phase, it's like playing two different octaves of the *A* notes together.

The time zones on the Earth are an example of phase differences. When it's 9 a.m. 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 in a glass of water and look through the side of the glass, you'll notice that the pencil appears to have shifted. The speed of light is slower in the water (140,000 miles per second) than in the air (186,000 miles per second). This is 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 the very point about refraction: when light enters a new substance (like going from air to water) perpendicular to the surface (looking straight on), refraction does not occur.

However, if you look at the glass at an angle, 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

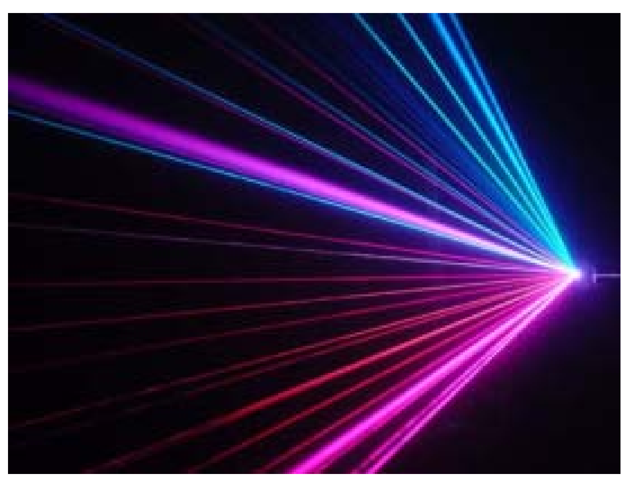
This means that if you place a Pyrex container inside a beaker of vegetable oil or Karo syrup, it will disappear (this also works for some mineral oils). Note, however, that the optical densities of liquids vary with temperature and concentration, and manufacturers are not perfectly consistent when they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

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

Lasers

The word "LASER" stands for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. 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 might bounce all over the place. You'd have half of the kids with very high-energy levels, while the other half would be sitting down in a lower energy state. The sugar-kids' energy would be infectious, though, and pretty soon, the rest of the kids would be 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 CD player 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.

