

# INTERFERENCE AND DIFFRACTION OF LIGHT

## STEP-UP PROGRAM SUMMER 2014

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### Problem:

What are the principles behind the interference and diffraction of light? What are examples of these interactions and how can they be used beneficially?

### Abstract:

The duality of light waves can sometimes be a difficult concept for high school level students to understand. To help demonstrate this dual personality the photoelectric effect often is used to show light acting as a particle (photons) and interference and diffraction can depict light's wave nature. However, at a high school level these principles can be difficult to apply and describe in the classroom. This lesson plan focuses on the wave nature of light and utilizes real-world examples and straightforward activities to explain the complexities of interference patterns and the diffraction of electromagnetic waves.

### Objectives:

- 1) Identify in which interference and diffraction will occur.
- 2) Describe how electromagnetic waves interfere with one another to create bright and dark fringes.
- 3) Solve problems using constructive and destructive interference equations.
- 4) Describe how electromagnetic waves diffract (bend) around objects and create bright and dark fringes.
- 5) Predict the locations of bright and dark fringes caused by diffraction using the diffraction equation.
- 6) Describe how diffraction is related to an optical instrument's resolution.
- 7) Describe what a Morie' pattern is and how it is formed.
- 8) Recognize real-world applications of interference and diffraction of light.
- 9) Describe the properties of lasers and their applications.

### Anticipated Learner Outcomes:

After the completion of this unit the student should be able to:

- 1) Describe the conditions for the interference and diffraction of light to occur.
- 2) Explain the principles behind interference and diffraction of light mathematically and conceptually.
- 3) Describe the superposition of light waves and how interference patterns are produced.
- 4) Solve for the path difference, wavelength and angle for constructive and destructive interference.
- 5) Relate the equations  $d \sin \theta_{\text{calc.}} = m \lambda$  and  $y = L \tan \theta_{\text{obser}}$  to solve for the path angle of a diffraction grating.

- 6) Describe how interference and diffraction of light is used in modern research and technology.
- 7) Describe how Moiré' patterns are formed and names Moiré' patterns found in nature.
- 8) Describe how lasers work and how they are used in real-world applications.

**Materials and Supplies: (These are only suggested supplies; most demonstrations can be found in video form if needed)**

- 1) Red laser pointers (one per group)
- 2) Green laser pointer (just for demonstration purposes)
- 3) 2 identical pocket combs
- 4) 2 pieces of window screen
- 5) 2 transparencies (copied with pattern from [http://www.exploratorium.edu/snacks/moire\\_patterns/index.html](http://www.exploratorium.edu/snacks/moire_patterns/index.html) )
- 6) Diffraction gratings with different grating sizes (I used 100 lines/mm, 300 lines/mm, 530 lines/mm, and 600 lines/mm, but as many and as varied of sizes that are available can be substituted) (one per group)
- 7) CD/DVD's without the aluminum coating and cut in pieces about 3 cm x 3 cm in size. Refer to teacher's answer key for the lab to demonstrate the easiest way to do this. (one per group)
- 8) Ring stands and clamps (one per group)
- 9) Rulers and Meter sticks (one per group)
- 10) Spectroscopes or diffraction gratings
- 11) Various light sources (LEDs, incandescent, fluorescent, halogen, sunlight, etc.)
- 12) Emission tube box and various emission tubes (hydrogen, helium, argon, neon, etc.)
- 13) \*Clear Nail Polish
- 14) \*Black construction paper
- 15) \*Aluminum cooking pan (large enough to hold and submerge the paper)
- 16) \*Water

\*Alternative Activity

**Plan: (This plan is designed for ten days\* with 50 minute periods but can be adapted for any schedule)**

Sections of the lesson plan (especially the PowerPoints) can be added on to, deleted or modified to meet curriculum needs or time restraints. Everything in bold is either included in this document or is in a separate heading that should be included. Note about PowerPoints: I usually print out the PowerPoints as notes for my students (that is why they are wordy) and then have them highlight certain points and write extra notes. They can be edited to meet your note-taking teaching style. Also, I am including shorter PowerPoints on each topic so they can be used in a flipped classroom and a list of optics websites.

**Day 1:**

- 1) Introduction to Interference. Refer back to sound waves and beats.
- 2) Begin the PowerPoint Presentation on **Interference**. Point out to students that different people use different language when speaking of the same thing. For example bright fringes can also be referred to as maxima or maximum, dark fringes are sometimes called minimum fringes and the

central bright fringe is sometimes thought of as the zero-order bright fringe. Also point out that with dark fringes the order number is one less than described because it is a half-step. For example: the first dark fringe is in between the central bright fringe ( $m = 0$ ) and the first bright fringe ( $m = 1$ ) so the 1<sup>st</sup> dark fringe ( $m + \frac{1}{2}$ ) is ( $0 + \frac{1}{2}$ ). This idea can be confusing for the students and should be emphasized.

- 3) Demonstrate Moiré' Patterns (a good site for demonstration ideas is [http://www.exploratorium.edu/snacks/moire\\_patterns/index.html](http://www.exploratorium.edu/snacks/moire_patterns/index.html) )
- 4) Remind the students about the diffraction of waves (water waves around an island, sound waves around an open door, etc.).
- 5) Demonstrate diffraction grating and red and green laser; see **Interference and Diffraction Demonstrations**

#### Day 2:

- 1) Begin the PowerPoint Presentation **Diffraction**. With spectroscopes point out how useful a tool they are and even though the ones that are used in the classroom involve visible light there are many spectrometers that use other portions of the electromagnetic spectrum.
- 2) If time permits pass out **Introduction to the Interference and Diffraction of Light Worksheet**.
- 3) These questions can be done as a class, in groups, or individually. They can be reviewed by the teacher or students can direct the discussion. This can be given as homework or in class.

#### Day 3:

- 1) Complete or review **Introduction to the Interference and Diffraction of Light Worksheet**
- 2) Demonstrate examples of Interference and Diffraction problems; see **Interference and Diffraction Demonstrations**
- 3) If time permits pass out **Interference and Diffraction Problems**.
- 4) These problems can be done as a class, in groups, or individually. They can be reviewed by the teacher or students can put the answers on the board. This can be given as homework or in class.

#### Day 4:

- 1) Complete the Worksheet: **Interference and Diffraction Problems**.

#### Day 5:

- 1) Review and Explain Procedures of the **Diffraction Grating Lab**.
- 2) Time remaining may be devoted to or unit projects.

#### Day 6:

- 1) Review and Explain Procedures of spectroscopy; see **Interference and Diffraction Demonstrations**. A spectroscopy lab can be done here, but most students should have done a spectroscopy lab in chemistry. I have included YouTube videos which are good reviews of spectroscopy. I have also included some videos on diffraction, interference and lasers which would all make good reviews.
- 2) **Spectroscopy Videos:** rhrcrgvp channel

- a. **Astronomy-spectroscopy-1/3 (9:59):** good basics on light and spectroscopy, speaks on Kirchoff's Laws of the continuous, emission, and absorption spectrum (focus mainly on emission)
  - b. **Astronomy-spectroscopy-2/3 (9:47):** continuation of the series and speaks more on the continuous spectrum; relates temperature to the spectra and the Balmer series
  - c. **Astronomy-spectroscopy-3/3 (8:03):** last part of the series; most related to astronomy; speaks of Doppler Effect and red/blue shifts.
- 3) **Diffraction and Interference Videos:** 1vertasium channel  
(<http://en.wikipedia.org/wiki/Veritasium>)
- a. **The Original Double Slit Experiment (7:40):** Starts off with the host asking people on the street – “What is Light?”; Young’s Double Slit Experiment with sunlight; interference patterns created in water; debate over light as waves and particles – watch till the very end – remind the students of the duality of light
  - b. **How to Make Color with Holes (5:38):** Light basics; combining of electric and magnetic fields; butterfly wings and their structure of scales – like diffraction gratings; soap bubbles
- 4) **Laser Videos:** SmarterEveryDay channel (done by a Huntsville missile engineer and a Dutch laser expert) Remind the students that these are professionals and they are using Class 4 lasers so a standard laser pointer will not work. Also, remind students that laser training and safety is very important.
- a. **How Lasers Work (in practice) – Smarter Every Day 33 (3:54):** open cavity laser
  - b. **Lasers vs. Balloons – Smarter Every Day 35 (4:28):** Class 4 laser is shone on different colored balloons (they all pop except the white one – the blue one does take longer); he explains why
  - c. **How to Light a Match Inside a Balloon – Smarter Every Day 36 (2:13):** Lights a match inside a white balloon with a Class 4 laser and the balloon does not pop.
- 5) **Holograms:**
- a. **How It’s Made: Holograms from the Discovery channel (EVAN199)(4:50):** self-explanatory

#### Day 7:

- 1) Begin the PowerPoint on **Diffraction and Optical Instruments**. Point out the diffraction limit of microscopes and how scientist use Fluorescence and Super-resolution Microscopes to “see” even finer details of a specimen.
- 2) Pass out **Microscope Internet Scavenger Hunt** worksheet. Have students use computers or SmartPhones to answer the questions. This can also be done for homework and the alternative activity can be done. I have also included a list of **Interactive Websites for Optics** that can be used in place of the Microscope Internet Scavenger Hunt, if other optics titles are more suited for a particular class.
- 3) **ALTERNATIVE ACTIVITY:** STEAM (Science Technology Engineering Art and Mathematics) **Thin-film Interference Activity (based on**  
<http://www.exo.net/~pauld/activities/light/interference/permanentoilslick.html>

**Day 8:**

- 1) See **Team Trivia: Interference and Diffraction** for instructions and questions. There is also a **PowerPoint** presentation if you have a SmartBoard with a clicker system.

**Day 9:**

- 1) **Unit projects** are due.
- 2) Have the students present their posters and flash charts to the class.
- 3) As the students are presenting ask them pertinent questions as a review.

**Day 10:**

- 1) Pass out **Interference and Diffraction Evaluation**.
- 2) The equations for the unit may or may not be provided.
- 3) The Evaluation can be counted as a quiz or a test.
- 4) The Evaluation should be graded at the teacher's discretion

**National Standards:**

**Content Standard A:** As a result of activities in grades 9-12, all students should develop:

- o Abilities necessary to do scientific inquiry
- o Understandings about scientific inquiry

**Content Standard B:** As a result of activities in grades 9-12, all students should develop an understanding of:

- o Structure and properties of matter
- o Interactions of energy and matter

**Content Standard G:** As a result of activities in grades 9-12, all students should develop an understanding of:

- o Science as a human endeavor
- o Nature of scientific knowledge

**PS 4: MOTIONS AND FORCES**

- d) Electricity and magnetism are two aspects of a single electromagnetic force. Moving electric charges produce magnetic forces, and moving magnets produce electric forces. These effects help students to understand electric motors and generators.

**PS 5: CONSERVATION OF ENERGY AND THE INCREASE IN DISORDER**

- a) All energy can be considered to be either kinetic energy, which is the energy of motion; potential energy, which depends on relative position; or energy contained by a field, such as electromagnetic waves.

**PS 6: INTERACTIONS OF ENERGY AND MATTER**

- a) Waves, including sound and seismic waves, waves on water, and light waves, have energy and can transfer energy when they interact with matter
- b) Electromagnetic waves result when a charged object is accelerated or decelerated. Electromagnetic waves include radio waves (the longest wavelength), microwaves, infrared radiation (radiant heat), visible light, ultraviolet radiation, x-rays, and gamma rays. The energy of electromagnetic waves is carried in packets whose magnitude is inversely proportional to the wavelength.
- c) Each kind of atom or molecule can gain or lose energy only in particular discrete amounts and thus can absorb and emit light only at wavelengths corresponding to these amounts. These wavelengths can be used to identify the substance.

## Georgia Performance Standards (Physics):

### SCSh1. Students will identify and investigate problems scientifically.

- a. Suggest reasonable hypotheses for identified problems.
- b. Develop procedures for solving scientific problems.
- c. Collect, organize and record appropriate data.
- d. Graphically compare and analyze data points and/or summary statistics.
- e. Develop reasonable conclusions based on data collected.
- f. Evaluate whether conclusions are reasonable by reviewing the process and checking against other available information.

### SCSh2. Students will use standard safety practices for all classroom laboratory and field investigations.

- 1. Follow correct procedures for use of scientific apparatus.
- 2. Demonstrate appropriate technique in all laboratory situations.
- 3. Follow correct protocol for identifying and reporting safety problems and violations.

### SCSh3. Students will identify and investigate problems scientifically.

- g. Suggest reasonable hypotheses for identified problems.
- h. Develop procedures for solving scientific problems.
- i. Collect, organize and record appropriate data.
- j. Graphically compare and analyze data points and/or summary statistics.
- k. Develop reasonable conclusions based on data collected.
- l. Evaluate whether conclusions are reasonable by reviewing the process and checking against other available information.

### SCSh6. Students will communicate scientific investigations and information clearly.

- a. Write clear, coherent laboratory reports related to scientific investigations.
- b. Write clear, coherent accounts of current scientific issues, including possible alternative interpretations of the data.
- c. Use data as evidence to support scientific arguments and claims in written or oral presentations.
- d. Participate in group discussions of scientific investigation and current scientific issues.

### SCSh9. Students will enhance reading in all curriculum areas by:

- a. Reading in All Curriculum Areas
  - Read technical texts related to various subject areas
- c. Building vocabulary knowledge
  - Demonstrate an understanding of contextual vocabulary in various subjects.
  - Use content vocabulary in writing and speaking.
  - Explore understanding of new words found in subject area texts.
- d. Establishing context
  - Explore life experiences related to subject area content.
  - Discuss in both writing and speaking how certain words are subject area related.
  - Determine strategies for finding content and contextual meaning for unknown words.

### SP3. Students will evaluate the forms and transformations of energy.

- a. Analyze, evaluate, and apply the principle of conservation of energy and measure the components of work-energy theorem by
  - • describing total energy in a closed system.
  - • identifying different types of potential energy.
  - • calculating kinetic energy given mass and velocity.
  - • relating transformations between potential and kinetic energy.
- b. Explain the relationship between matter and energy.
- e. Demonstrate the factors required to produce a change in momentum.

**SP4. Students will analyze the properties and applications of waves.**

- a. Explain the processes that results in the production and energy transfer of electromagnetic waves.
- b. Experimentally determine the behavior of waves in various media in terms of reflection, refraction, and diffraction of waves.
- c. Explain the relationship between the phenomena of interference and the principle of superposition.
- e. Determine the location and nature of images formed by the reflection or refraction of light.

## Background:

### Interference:

When two waves with equal wavelengths cross paths, they will combine to form a resultant wave. The resultant wave has the same wavelength as the two interacting waves, but its displacement at any point equals the algebraic sum of the displacements of the component waves (superposition principle). The formation of the resultant wave is caused by the **interference** of the two individual waves. Interference can be destructive or constructive depending on if the displacements are in opposite or in the same directions.

Constructive interference is demonstrated when using **monochromatic** light (one wavelength/color), if the light waves combine to form a resultant wave with amplitude that is larger than the individual waves. For light, the resultant wave will be brighter than the two individual waves. In the case of destructive interference, the amplitude of the resultant wave is less than that of the individual waves and will result in dimmer light or no light at all (complete destructive interference).

For an interference pattern to be seen on a screen, the light waves reaching any point on the screen must have a phase difference that does not change in time. These waves are said to have **coherence** (the property by which two waves with the same wavelength will maintain a constant phase relationship). This is the reason that **lasers** (an instrument that produces an intense, parallel beam of coherent light) are a great light source for this lab. The monochromatic light passes through two very small and parallel slits. When the light from the two slits arrives at a point on a screen, constructive or destructive interference will occur. As a result, either a bright or dark band (fringe) will appear on the screen. See Figure 1.

When both waves of light move the same distance, they appear on the screen in phase and interfere constructively. The waves will also interfere constructively (bright fringes) if the difference between the distances traveled by each light source equals a whole wavelength. However, if the differences in the distances traveled by the light are equal to a half a wavelength, destructive interference (dark fringes) will occur.

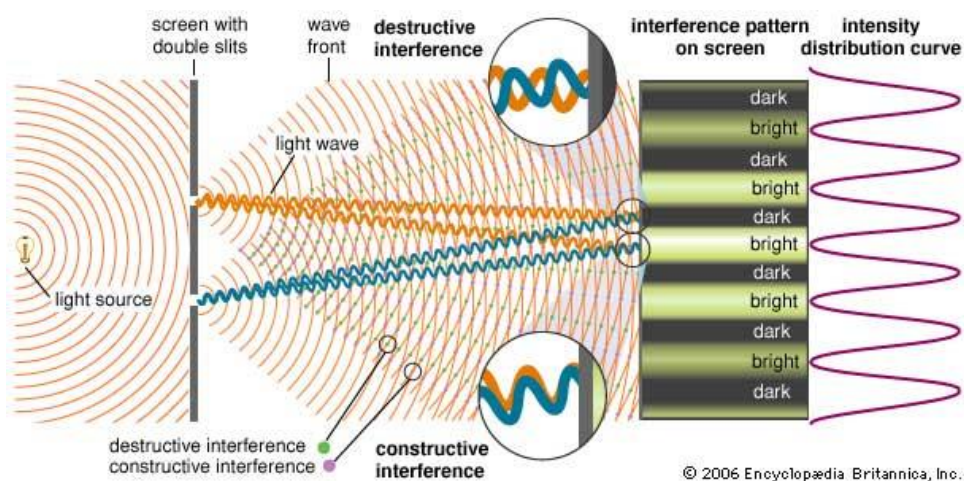


Fig. 1

Double Slit  
interference  
patterns

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<http://www.britannica.com/EBchecked/topic-art/340440/91986/Youngs-double-slit-experiment-When-monochromatic-light-passing-through-two#tab=active~checked%2Citems~checked>

## Diffraction:

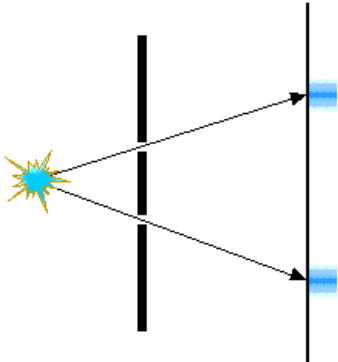
**Diffraction** refers to the behavior of waves bending around obstacles or that pass through small openings. Though light waves are able to diffract like other waves, it can be difficult to observe due to their very small wavelengths [visible light range:  $700 \text{ nm (red)} > \lambda > 400 \text{ nm (violet)}$ ]. If light were only a particle and did not diffract it would travel in straight lines and an interference pattern would not be observed in the double-slit demonstration (See INTERFERENCE and FIG. 2). The bending of light as it passes through each of the two slits can be explained through **Huygens' Principle\*** (any point on a wave front can be treated as a point source of waves). Since each slit serves as a point source of light, the light waves spread out from the slits and depart from the straight-line path.

Diffraction patterns result from constructive and destructive interference and therefore resemble interference patterns. However, in the case of interference the slits behave as point sources of light, whereas for diffraction, the actual width of a single slit is taken into consideration. The amount the light that will bend is determined by the relative size of the light's wavelength compared to the size of the barrier or opening. If the opening is much greater than the light's wavelength, the bending will be almost undetectable. However, if the size difference is small, the amount of light that will bend will be quite easy to view.

\*This is an interesting link in learning to pronounce Huygens' name: <http://frank.harvard.edu/~paulh/misc/huygens.htm>

## The Two Logical Possibilities

1. If light consists of particles.



2. If light consists of waves.

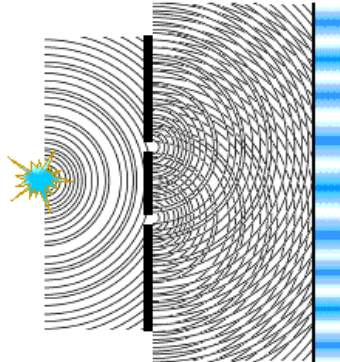


Fig. 2

Discuss the dual nature of light

<http://www.bottomlayer.com/bottom/reality/images/lightslitpossible.GIF>

A **diffraction grating** is a device that uses the principles of diffraction and interference to separate light into its component colors producing an effect comparable to that of a prism. Diffraction gratings can be constructed to either transmit or reflect light. A **transmission** grating (light is able to pass through) is comprised of many equally spaced parallel slits. Reflection gratings can both be plane or concave and reflect the incident light at different angles to produce a diffraction pattern (the rainbow of colors that appear on the surface of a CD).

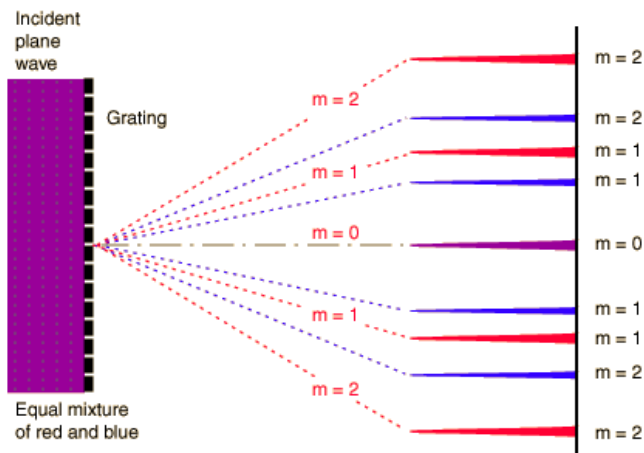


Fig. 3

Transmission Diffraction Grating

Light of a single wavelength passes through each of the slits of a diffraction grating to constructively interfere at a particular angle.

<http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/grating.html>

The condition for the bright fringes is the same in the diffraction grating as that of the double-slit example. However, angular separation of the bright fringes is usually much larger because the slit spacing is so small for a diffraction grating. The greater the number of lines per unit of length in a grating, the smaller the distance between the slits and the farther spread apart the individual wavelengths of light are.

The bright fringe formation is given by the equation for constructive interference:

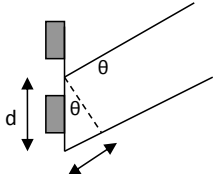


Fig 4a

$$d(\sin\theta) = m\lambda$$

$$m = 0, \pm 1, \pm 2, \dots$$

Eqn 1

$d$  = distance between slits

$\theta$  = angle of diffraction

$\lambda$  = wavelength of light

$m$  = the order number for the bright fringes

Let  $\theta$  represent the angle of diffraction of the beam with respect to the incident direction. Let  $d$  be the spacing between the two slits. The path difference between the two waves starting from the two slits, as in Fig. 4a and b. can be clearly shown to be  $d \sin \theta$ . For these waves to constructively interfere the waves must arrive in phase; clearly the path difference has to be an integral multiple of the wavelength.

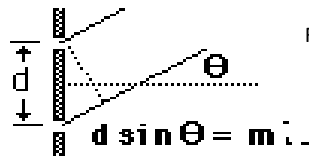


Fig. 4 b

<http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/grating.html>

## CDs and DVDs as DIFFRACTION GRATINGS

CDs and DVDs show a display of colors when white light falls on them. This is due to the digital information (alternating pits and smooth reflecting surfaces) on the discs forming closely spaced rows acting like reflecting diffraction grating. These rows are spaced 1.6 micrometers from one another on a CD and 0.74 micrometers on a DVD. These rows do not reflect nearly as much light as the portions of the disc that separate them. In these portions the light reflected undergoes constructive interference in certain directions. Therefore, when white light is reflected from the disc each wavelength of light can be seen at a particular angle with respect to the disc's surface producing a light spectra.

CDs and DVDs have a protective polycarbonate coating which does not interfere in the reflective diffraction grating, but to create a transmission grating the metal layer must be removed and the physical diffraction grating retrieved. This is a crucial step if AFM images are to be produced (See AFM). DVDs are usually two layered which are fairly easy to separate. CDs are one layer and cannot be separated so other techniques must be applied. (See ADVANCED PREPARATIONS)

To listen to a CD, the laser light in the CD player is reflected consecutively from the thread of binary bits etched on the disc (alternating pits and smooth, reflecting surfaces). When the light reflects from the smooth surface it reaches the detector. However, when the light reflects from the pits it is out of phase and the intensity of the beam hitting the sensor is less (the depth for the pits is roughly about one quarter of the wavelength of the laser). Any change in the intensity of the reflected beam as it transitions from a pit to land or land to pit is converted to an electrical signal and coded as a binary 1. Electronic circuits connected to the detector translate the binary data into an electrical signal. The

signal is then amplified and results in a reconstruction of the original recorded sample. A DVD player works on the same principle, but uses a smaller wavelength laser and therefore can detect information that is coded in much smaller pits and smooth, reflecting surfaces. DVDs can hold more than seven times as much data as a CD.

### Spectroscopy:

A **spectroscope** is a tool that is used to determine the composition of materials by breaking down the light emitted or absorbed by chemical elements into particular lines of color (spectra). Light (electromagnetic radiation) is created when an excited electron moves back to its lower energy level from a higher energy level. The photon of light that is released has an energy that matches exactly to the difference in energy between the two orbits. Every chemical element has its own unique “fingerprint” of these orbitals that can be used to identify the chemical composition.

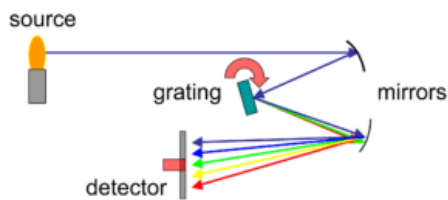


Fig. 5; Parts of a simple spectroscope

<http://en.wikipedia.org/wiki/Spectrometer>

### Continuous Spectra:

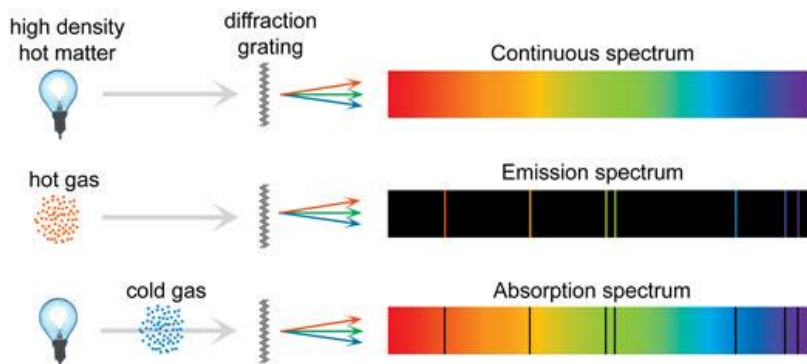
Shows all the colors of the rainbow blended into one another in a band. They are usually produced by a luminous liquid or solid. Ex) glowing filament of an incandescent bulb.

### Absorption Spectra:

A dark line spectra which is identified by the black bands of missing color present in a continuous spectra. They are generated when white light passes through a cooler gas located between the source of the continuous spectrum and the observer. The cooler gas absorbs those wavelengths that it would usually emit if it were the glowing source. It has the same spectral “fingerprint” that the cooler gas would if it were emitting a bright line spectrum. Think of it like a photo-negative.

### Emission Spectra:

Or Bright line emission spectra, whose source is a glowing gas. This gas emits photons with very specific energies (frequencies or wavelengths) that are characteristic of the chemical element of which the gas is composed of. Stars and tubes of heated gas can produce this emission spectra. A continuous emission spectra is produced by the chemicals in hot, incandescent gas and displays bright bands of color on top of a continuous spectra. You can see this spectra when looking at florescent lights. The white coating on the bulb mixes the elemental lines of the gas inside the bulb to create the continuous spectra while the bright bands are produced from the gas inside.



Images courtesy of Mark Tiele Westra;  
<http://www.scienceschool.org/2007/issue4/spectrometer>

Fig. 6



Helium



Hydrogen

Fig. 7 a and b; Emission spectrum of Helium and Hydrogen

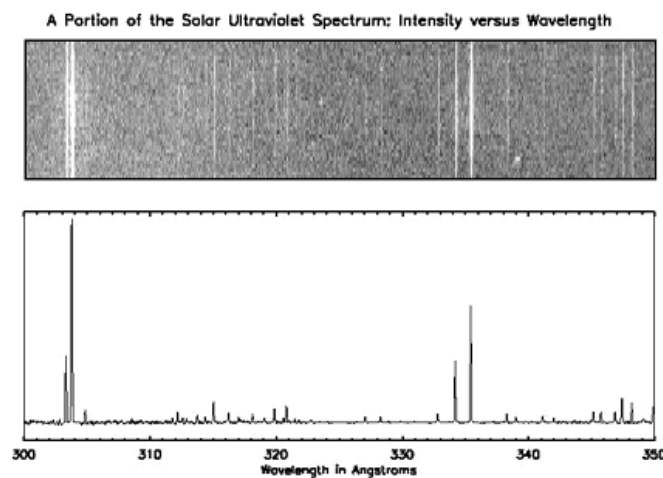


Fig. 8 a and b; A graphical representation of a line spectrum.

### More on the Emission Line Spectra

Unlike a continuous spectrum source, which can have *any* energy it wants (all you have to do is change the temperature), the electron clouds surrounding the nuclei of atoms can have only very specific energies dictated by quantum mechanics. Each element on the periodic table has its own set of possible energy levels, and with few exceptions the levels are distinct and identifiable.

Atoms will also tend to settle to the lowest energy level (*ground state*). This means that an excited atom in a higher energy level must 'dump' some energy. The way an atom 'dumps' that energy is by emitting a wave of light with that *exact* energy.

In the diagram following, a hydrogen atom drops from the 2nd energy level to the 1st, giving off a wave of light with an energy equal to the difference of energy between levels 2 and 1. This energy corresponds to a

specific color, or wavelength of light -- and thus we see a bright line at that *exact* wavelength! ...an *emission spectrum* is born, as shown below:

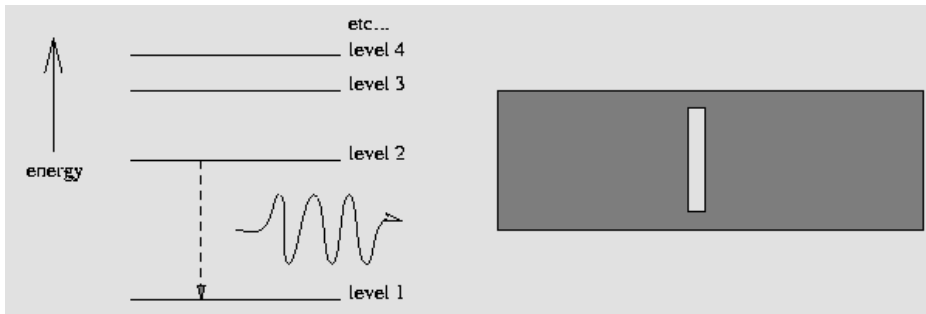


Fig. 9; An excited Hydrogen atom relaxes from level 2 to level 1, yielding a photon. This results in a bright *emission* line. [http://loke.as.arizona.edu/~ckulesa/camp/spectroscopy\\_intro.html](http://loke.as.arizona.edu/~ckulesa/camp/spectroscopy_intro.html)

Tiny changes of energy in an atom generate photons with small energies and long wavelengths, such as radio waves! Similarly, large changes of energy in an atom will mean that high-energy, short-wavelength photons (UV, x-ray, gamma-rays) are emitted.

### Absorption Line Spectra

On the other hand, what would happen if we tried to reverse this process? That is, what would happen if we fired this special photon back into a ground state atom? That's right, the atom could absorb that 'specially-energetic' photon and would become excited, jumping from the ground state to a higher energy level. If a star with a 'continuous' spectrum is shining upon an atom, the wavelengths corresponding to possible energy transitions within that atom will be absorbed and therefore an observer will not see them. In this way, a *dark-line absorption spectrum* is born, as shown below:

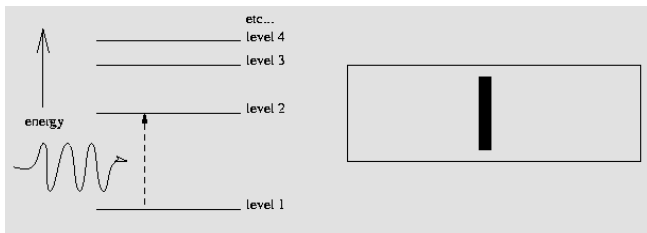


Fig. 10; A hydrogen atom in the ground state is excited by a photon of exactly the 'right' energy needed to send it to level 2, absorbing the photon in the process. This results in a dark *absorption* line. [http://loke.as.arizona.edu/~ckulesa/camp/spectroscopy\\_intro.html](http://loke.as.arizona.edu/~ckulesa/camp/spectroscopy_intro.html)

### Fields that use Spectroscopy:

#### Astronomy:

Most astronomers are not continuously looking through their large telescopes, because they are letting the telescopes collect light for a spectrograph. Since each type of atom (or ion) has its own wavelength that it can absorb or emit, they will produce a unique spectra. The temperature of a star varies, so the atoms in the outer, cooler layers of the star absorb light emitted from the inner, hotter layers. This produces a dark absorption line across the spectrum. This spectra is used to identify the make-up of atoms in a star. Unlike a

spectroscope used in school, astronomers do not take a color picture of the spectrum for the following reasons:

- a) Color film is less sensitive than black and white.
- b) Color film does not represent the continuous range of colors in a spectrum very well.
- c) A graph showing brightness vs. wavelength has a lot more quantitative information

Thus astronomers make graphs of their spectra, with the y-axis showing the brightness, while the x-axis shows the wavelength. In the figure this graph is aligned just below the picture of the spectrum.

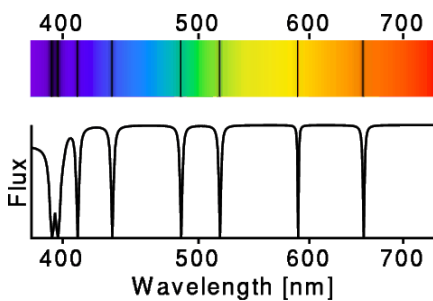


Fig. 11 a and b; Spectrum and Spectrograph

<http://www.astro.ucla.edu/~wright/fluxplot.html>

Not only can astronomical spectroscopy be used to figure out a star's chemical composition it can also determine temperature, luminosity, density, distance, mass and relative motion using the Doppler Effect.

### Gemology:

The way that transparent, colored gemstones absorb the visible light that passes through them is what determines their color. The color observed is directly related to the stones chemical make-up, spectroscopy is a very effective method for determining the chemistry of the gemstones.



Fig. 12; Spectra of various gemstones

<http://www.suncoastgemlab.com/blog/2013/01/gem-notes-gemological-spectroscopy/>

## Chemistry (also Physics and Biology):

Research scientists use spectroscopy often regardless of their field. The spectra can be used to identify the composition of the sample and the amounts of the chemicals in the sample, but other information can also be obtained. For example, information about atomic and molecular energy levels, chemical bonds, interactions of molecules and the shapes of the molecules can also be determined. Usually the spectrum is a plot of the intensity of the energies versus the wavelength, frequency, mass, momentum, etc. of the energy.

## Types of Spectroscopy:

There are many types of spectroscopy used, but I just chose a few to discuss. The site:

<http://chemistry.about.com/od/analyticalchemistry/a/spectroscopy.htm> is a good place to start to learn about other types. It would be a good extension to this unit to have the students report on the different types of spectroscopy and could replace the Unit Project if desired. Spectroscopy is used so much in research it is really an important topic.

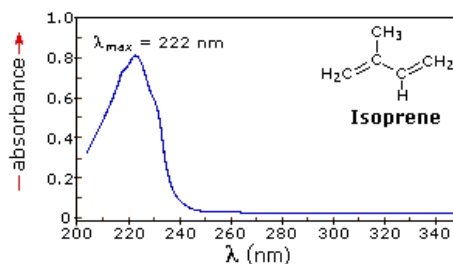
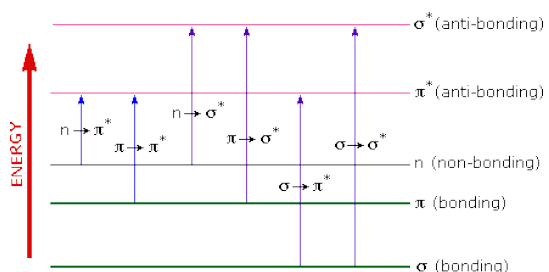
## Visible and Ultraviolet Spectroscopy:

Different compounds can be differentiated by their color. For example, chlorophyll is green and quinone is yellow. In this respect our eyes act as a spectrometer that detects and analyzes the light reflect from an opaque object or transmitted through a transparent one. To understand why some compounds have color and others do not, precise measurements of light absorption at various wavelengths in and near the visible part of the electromagnetic spectrum are required.

The visible region of the spectrum comprises photon energies of 36 to 72 kcal/mole, and the near ultraviolet region, out to 200 nm, extends this energy range to 143 kcal/mole. This is enough energy to excite a molecular electron to a higher energy orbital. Usually, energetically favored electron promotion will be from the **highest occupied molecular orbital (HOMO)** to the **lowest unoccupied molecular orbital (LUMO)**, and the resulting species is called an **excited state**. When sample molecules are exposed to light having an energy that matches a possible electronic transition within the molecule, some of the light energy will be absorbed as the electron is promoted to a higher energy orbital. An optical spectrometer records the wavelengths at which absorption occurs, together with the degree of absorption at each wavelength. The resulting spectrum is

Fig. 13 a and b; Both images: <http://www2.chemistry.msu.edu/faculty/reusch/VirtTxtUml/Spectrpy/UV-Vis/spectrum.htm#uv1>

presented as a graph of absorbance (A) versus wavelength.



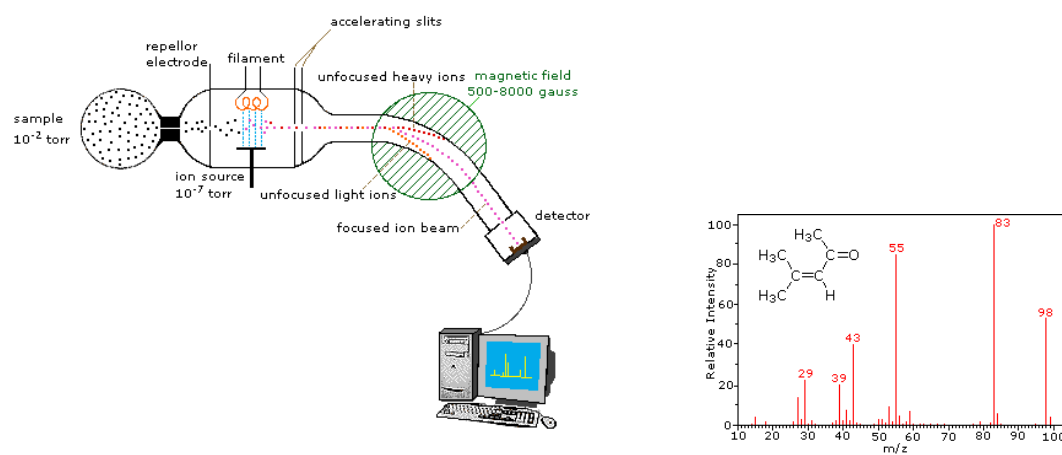
### **Mass Spectroscopy:**

A mass spectrometer converts individual molecules to ions so an external electric/magnetic field can manipulate them and the characteristics of the molecules can be determined. The three main parts of a mass spectrometer are:

- d) The Ion Source** (a sample is ionized – us. Loss of an e-)
- e) The Mass Analyzer** (the ions are separated based on their mass and charge)
- f) The Detector** (the ions are measured and results displayed)

Fig. 14 a and b; a) on the left shows the basic setup of a Mass Spectrometer and b) shows the graphical representation of the spectra

Both images from: <http://www2.chemistry.msu.edu/faculty/reusch/VirtTxtJml/Spectrpy/MassSpec/masspec1.htm#ms1>



### IR (Infrared):

Photon energies associated with this part of the electromagnetic spectrum are not great enough to excite electrons, but may induce vibrational excitation of covalently bonded atoms and groups. The covalent bonds in molecules are not rigid sticks or rods, such as found in molecular model kits, but are more like stiff springs that can be stretched and bent. Molecules experience a large variety of vibrational motions, characteristic of their component atoms. Consequently,

virtually all organic compounds will absorb infrared radiation that corresponds in energy to these vibrations. This allows researchers to obtain absorption spectra of compounds that are a unique reflection of their molecular structure.

One influence of the intensity of infrared absorptions, is that a change in dipole moment should occur for a vibration to absorb infrared light. Absorption bands associated with C=O bond stretching are usually very strong because a large change in the dipole takes place in that mode.

#### Some General Trends:

- a) Stretching frequencies are higher than corresponding bending frequencies. (It is easier to bend a bond than to stretch or compress it.)
- b) Bonds to hydrogen have higher stretching frequencies than those to heavier atoms.
- c) Triple bonds have higher stretching frequencies than corresponding double bonds, which in turn have higher frequencies than single bonds.  
(Except for bonds to hydrogen).

#### Gas Phase Infrared Spectrum of Formaldehyde, $\text{H}_2\text{C}=\text{O}$

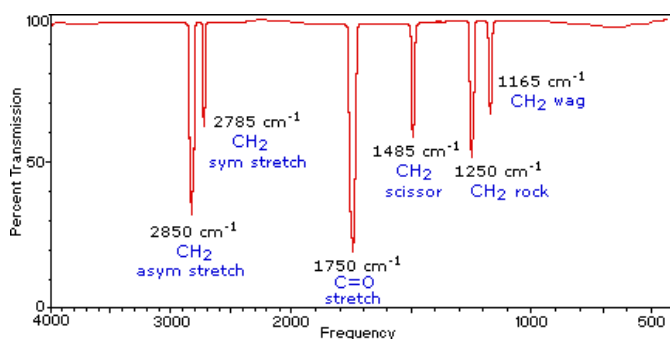


Fig. 15; shows the IR spectrograph of Formaldehyde;

<http://www2.chemistry.msu.edu/faculty/reusch/VirtTxtJml/Spectrpy/InfraRed/infrared.htm>

#### Raman Spectroscopy:

Raman Spectroscopy: a technique used to detect vibrational, rotational and other low frequency modes in a sample. When electromagnetic radiation is scattered by a molecule, the incident photon is destroyed and, at the same time, another photon of the scattered radiation is created. The scattering mechanisms are grouped based on the difference between the energies of the incident and scattered photons. If the incident energy equals the scattered this is referred to as Rayleigh scattering (most types of scattering). However if the incident is different than the scattered energy (inelastic scattering – KE is not conserved) then it is known as Raman scattering.

The photon is the incident particle and interacts with matter and the frequency of the photon is shifted to red (energy of photon decreases) or blue (energy of photon increases). The molecular bonds and chemical make-up determine the Raman shift and spectra.

The Raman Effect occurs when light is incident on a molecule and interacts with the electron cloud and the bonds of the molecule. A photon excites the electron in the molecule from the ground state to a virtual energy state. As the molecule relaxes a photon is emitted and the electron returns to a different vibrational state. The change in energy from the initial state and the new state leads to a shift in the emitted photon's frequency.

If the final state is more energetic than the original, then the emitted photon will be shifted to a lower frequency to balance out the total energy of the system (Stokes shift). If the final state is less energetic, then the emitted photon will be shifted to a higher frequency (anti-Stokes shift). Some amount of deformation of the electron cloud is required for a molecule to exhibit a Raman effect.

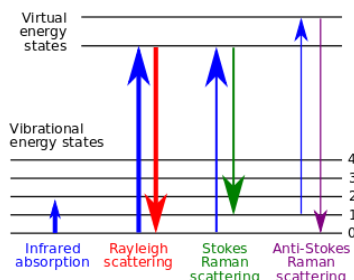


Fig. 16; Energy level diagram showing the states involved in Raman signal. The line thickness is roughly proportional to the signal strength from the different transitions.  
[http://en.wikipedia.org/wiki/Raman\\_spectroscopy](http://en.wikipedia.org/wiki/Raman_spectroscopy)

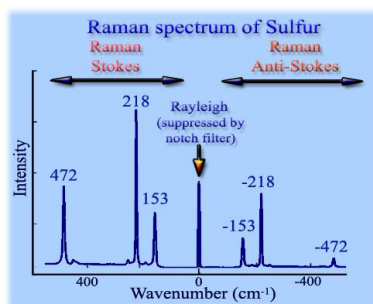


Fig. 17; Shows the Raman Spectrum of Sulfur; red shift is the Raman Stokes and the blue shift is the Raman Anti-Stokes  
[http://www.fis.unipr.it/phevix/raman\\_tutorial.html](http://www.fis.unipr.it/phevix/raman_tutorial.html)

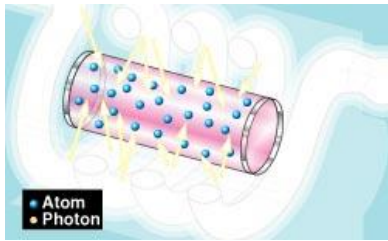
## Lasers and Holograms:

### Lasers:

A laser (Light Amplification by Stimulated Emission of Radiation) is an instrument that converts light, electrical or chemical energy into coherent light. Coherence means that the light waves interfere constructively causing them to have become in phase with one another (in-step). This increases the amplitude and therefore the energy of the laser.

There are many types of lasers but they all use an active medium to which energy is added to produce coherent light. The active medium can be solid, liquid, or gas. The composition of the active medium determines the wavelength, or color, of the light produced by the laser.

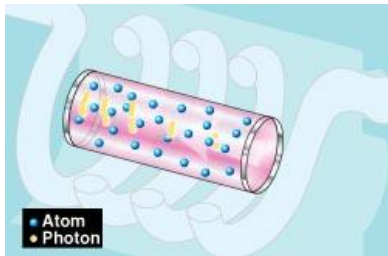
The following explanation and images (Fig. 18 a-d) are from the National Ignition Facility (NIF) a part of the National Nuclear Security Administration. < [https://lasers.llnl.gov/education/how\\_lasers\\_work.php](https://lasers.llnl.gov/education/how_lasers_work.php)>



a) High-voltage electricity causes the quartz flash tube to emit an intense burst of light, exciting some of the atoms in the ruby crystal to higher energy levels.



b) At a specific energy level, some atoms emit particles of light called photons. At first the photons are emitted in all directions. Photons from one atom stimulate emission of photons from other atoms and the light intensity is rapidly amplified.



c) Mirrors at each end reflect the photons back and forth, continuing this process of stimulated emission and amplification.



d) The photons leave through the partially silvered mirror at one end.

This is laser light.

The laser flash that escapes through the partially reflecting mirror lasts for only about 300 millionths of a second, but is very intense. Early lasers could produce peak powers of some 10,000 watts. Modern lasers can produce pulses that are billions of times more powerful.

The 1,000-watt light used in modern lighthouses can be seen from 20 miles away. But beyond that distance, the light beam has spread out so much that it is difficult to see. A laser beam, however, will run straight and true for very long distances. A laser beam has been bounced off the moon to accurately measure the distance of more than 250,000 miles! The beam stays roughly the same size as it travels this vast distance. Coherence means that laser light can be focused with great precision.

Many different materials can be used as lasers. Some, like the ruby laser, emit short pulses of laser light. Others, like helium–neon gas lasers or liquid dye lasers, emit a continuous beam of light. The NIF lasers, like the ruby laser, are solid-state, pulsed lasers.

Lasers have many important applications. They are used in common consumer devices such as DVD players, laser printers, and barcode scanners. They are used in medicine for laser surgery and various skin treatments, and in industry for cutting and welding materials. They are used in military and law enforcement devices for marking targets and measuring range and speed. Laser lighting displays use laser light as an entertainment medium. Lasers also have many important applications in scientific research.

### Holograms:

Holography is a technique that creates three-dimensional images. Interference and diffraction principles are used along with lasers, light intensity recording and suitable lighting of the recorded image to create a hologram. The image changes appearance as the position/orientation of the viewing system changes in the same way as if the object were still there (why the image appears 3-D).

Holography allows a light field, which is generally the product of a light source scattered off objects, to be recorded and later reconstructed when the original light field is no longer present, (the original object is absent). A good analogy is to think of holography like a sound recording. The sound field is created by vibrating objects (musical instruments or vocal cords) that is encoded in such a way that it can be reproduced later, without the original vibrating objects. The holographic recording itself is not an image; it consists of an apparently random structure of either varying intensity, density or profile.

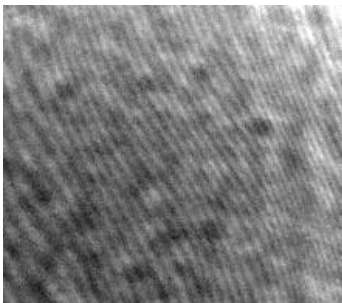


Fig. 19; Close-up photograph of a hologram's surface. The object in the hologram is a toy van. It is no more possible to discern the subject of a hologram from this pattern than it is to identify what music has been recorded by looking at a CD's surface. Note that the hologram is described by the speckled pattern, rather than the "wavy" line pattern. <http://en.wikipedia.org/wiki/Holography>

When the hologram plate is illuminated by a laser beam identical to the reference beam which was used to record the hologram, an exact reconstruction of the original object wave front is obtained. An imaging system (an eye or a camera) located in the reconstructed beam 'sees' exactly the same scene as it would have done when viewing the original. When the lens is moved, the image changes in the same way as it would have done

when the object was in place. A holographic image can also be obtained using a different laser beam configuration to the original recording object beam, but the reconstructed image will not match the original exactly. When a laser is used to reconstruct the hologram, the image is speckled just as the original image would have been. This can be a major drawback in viewing a hologram.

White light consists of light of a wide range of wavelengths. Normally, if a hologram is illuminated by a white light source, each wavelength can be considered to generate its own holographic reconstruction, and these will vary in size, angle, and distance. These will be superimposed, and the summed image will wipe out any information about the original scene, just as if you superimposed a set of photographs of the same object of different sizes and orientations. However, a holographic image can be obtained using white light in specific circumstances, e.g. with volume holograms and rainbow holograms. The white light source used to view these holograms should always approximate to a point source, i.e. a spot light or the sun. An extended source (e.g. a fluorescent lamp) will not reconstruct a hologram since its light is incident at each point at a wide range of angles, giving multiple reconstructions which will "wipe" one another out.

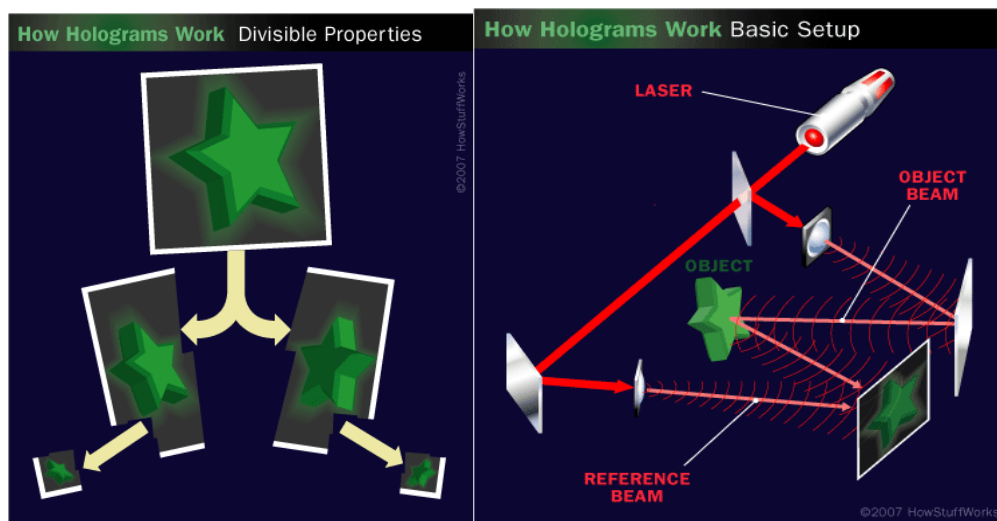


Fig. 20 a and b; a) on the left demonstrates the divisible properties of a hologram and b) on the right shows the basic setup for a transmission hologram. <http://science.howstuffworks.com/hologram.htm>

### Types of Holograms: This is just a few types

#### Transmission:

These can be found on credit cards and money. They are called transmission because they should be lit from behind (like a slide in a slide projector). It can be difficult to light the hologram in this manner so a mirror or a foil backs the hologram. This is why the credit card hologram has a silvery appearance. The light can bounce off the mirrored backing and basically light the hologram from behind.

A **rainbow hologram** is a special type of transmission hologram as the light being used to illuminate them is split into a spectrum, the hologram representing the 'correct' color(s) from one angle, while at other angles seen in different colors of the spectrum (from deep blue to red). Transmission rainbow holograms can be large ( $>1\text{m}^2$ ) or small ( $<10\text{mm}^2$ ), can be made singularly, or mass-reproduced using a technique known as **embossing**. **Embossed holograms** are the ones usually seen on credit cards and packaging. The original hologram is made into a metal copy and duplicates are used to create millions of copies by embossing the pattern into soft aluminized plastic. This the most common form of holography because it can be made in great quantities quickly and cheaply.



Fig. 21; Embossed holograms massed produced.

<http://www.holomall.com/Hologram%20Pictures.htm>

#### Reflection:

For this type of hologram the object and reference beams are incident on the plate from opposite sides of the plate. The reconstructed object is then viewed from the same side of the plate as that at which the re-constructing beam is incident. With a reflection holography, the image is stored in a thick emulsion and can be viewed in white light. The simplest such hologram to make is the direct beam reflection hologram. In this case the direct beam through the film serves as the reference beam.

Fig. 22; Setup of a direct beam reflection hologram;

<http://hyperphysics.phy-astr.gsu.edu/hbase/optmod/holog3.html>

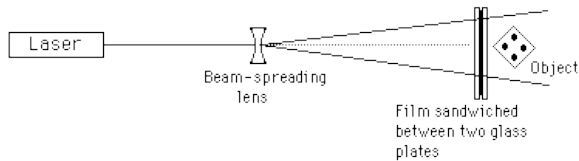


Fig. 23; An example of a reflection hologram; usually they are back painted so light is reflected

<http://digilander.libero.it/crispers/holograms.html>

### Pulsed:

A moving object can be made to appear to be at rest when a hologram is produced with the extremely rapid and high-intensity flash of a pulsed ruby laser. The duration of such a pulse can be less than  $1/10,000,000$  of a second; and, as long as the object does not move more than  $1/10$  of a wavelength of light during this short time interval, a usable hologram can be obtained. A continuous-wave laser produces a much less intense beam, requiring long exposures; thus it is not suitable when even the slightest motion is present.



Fig. 24; An example of a pulsed hologram; does not require the object to be completely stationary  
<http://www.holograms.bc.ca/home6b1.htm>

Sometimes the term **hologram** is used incorrectly. For example:

At the 2006 Grammy Awards the [Pepper's ghost technique](#) was used to project Madonna with the virtual members of the band Gorillaz onto the stage in a "live" performance. This type of system consists of a projector (usually DLP) or LED screen, with a very high resolution (1280x1024 or higher) and very high brightness (at least 5,000 lumens), a high-definition video player, a stretched film between the audience and the acting area, a 3D set/drawing that encloses three sides, plus lighting, audio, and show control.<sup>[13]</sup>

During [Dr. Dre](#) and [Snoop Dogg](#)'s performance at the 2012 [Coachella Valley Music and Arts Festival](#), a projection of deceased rapper [Tupac Shakur](#) appeared and performed "[Hail Mary](#)" and "[2 of Amerikaz Most Wanted](#)".<sup>[14][15]</sup>

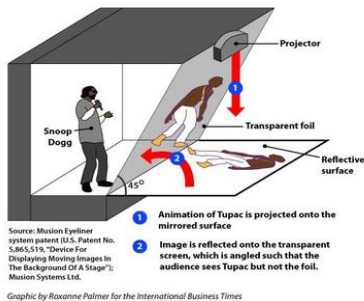


Fig. 25; A demonstration of how Tupac's image appeared – not a hologram  
<http://gizmodo.com/5903092/this-is-how-tupacs-hologram-that-wasnt-really-a-hologram-worked>

## Microscopy:

### History and Introduction to Basic Microscopy:

Though it has been known for over 2000 years that glass refracts light it was not until the first century that the Romans started doing actual experiments with glass. The Romans tested different shapes of glass and one shape was thin on the edges and thick in the center and when placed over an object it would appear larger. These primitive lenses were called magnifiers or burning glasses. The actual word lens came from the Latin term *lenticula*, due to the shape of the lens looking like a lentil bean. However, lenses were not in wide use until the end of the 13<sup>th</sup> century where they were made into glasses for better vision. Then around 1590, a father and son spectacle maker team (Hans and Zaccharias Janssen), started experimenting with lenses and combining them to find that there was increased magnification. These first microscopes were fairly weak (6x – 10x power) and used more for amusement than for any scientific study.

Finally in the late 17<sup>th</sup> century, Antony Van Leeuwenhoek, created the first practical microscope. He was able to create a lens with a magnification of 270 xs by grinding and polishing small glass balls. With this microscope he was able to see things that no one ever had seen before (bacteria, yeast, blood cells, etc.). This led to the thought that life might be made of smaller components that cannot be seen by the unaided eye. The problem was that to increase the power of a single-lens microscope, you would need to make the focal length smaller. This reduction requires that the lens diameter also be reduced which eventually becomes too hard to see through.

To go around the above conundrum, the compound microscope was created (still in the 17<sup>th</sup> century). This system utilizes more than one lens so that the image of one lens can be magnified further with another lens. The two main lenses are the eyepiece (lens closer to the eye) and the objective (lens closer to object). It is important to note that what is seen in a compound microscope is not a tangible object but an imaged formed from the combination of lenses.

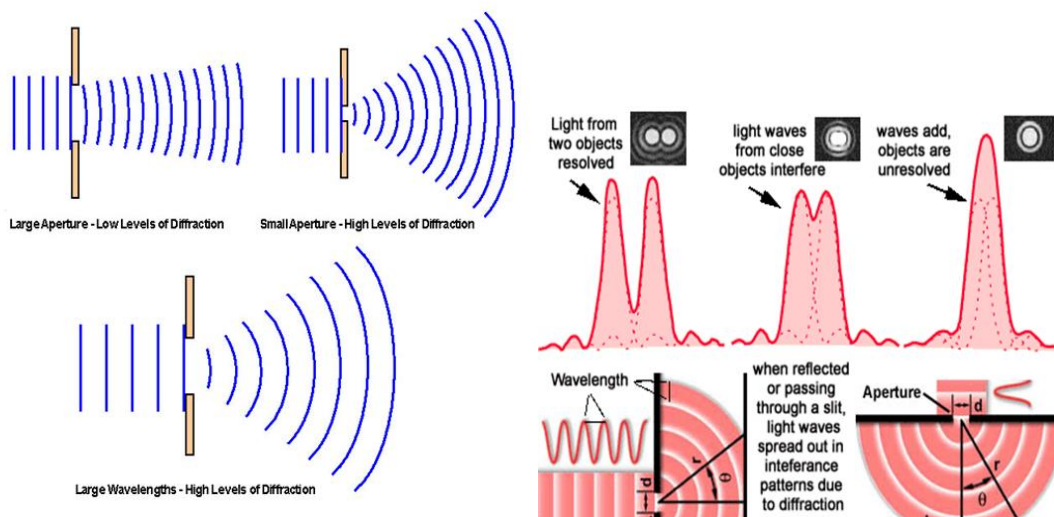
### Resolution and Magnification:

The goal of any microscope is to improve resolution. Resolution is the ability of an optical instrument is to resolve detail in the object that is being imaged. It is determined by wavelength of light and aperture width. The microscope's role is to increase the view of the object so details can be observed that are not possible with the unaided eye. Because of the increased size of the image, resolution is often mistaken for magnification. It is generally the case that a larger magnification leads to greater resolution, but this is not always true. The resolution of an optical instrument can be limited by factors such as flaws in the lenses or misalignment. However, there is a max to the resolution of any optical instrument due to diffraction.

Fig. 26 a; (left) Demonstrates how aperture size and wavelength affect the diffraction of light.

<http://www.imagen-estilo.com/Articles/Photography-basics/lens-diffraction-limit.html>

Fig. 26 b; Relates Resolution and Diffraction Limits. <http://www.xenophilia.com/zb0012a.htm>



It was not until the mid 1800's that more improvements were made to the microscope. There were three main issues with the microscope that had to be dealt with to improve the resolution of the microscope. The first problem was chromatic aberration. This is a distortion due to the fact that different colors of light bend at different angles through the lens and therefore do not focus at the same point. This problem was fixed (Chester Hall in the 1730's) by using a second lens of different shape that would realign the light colors.

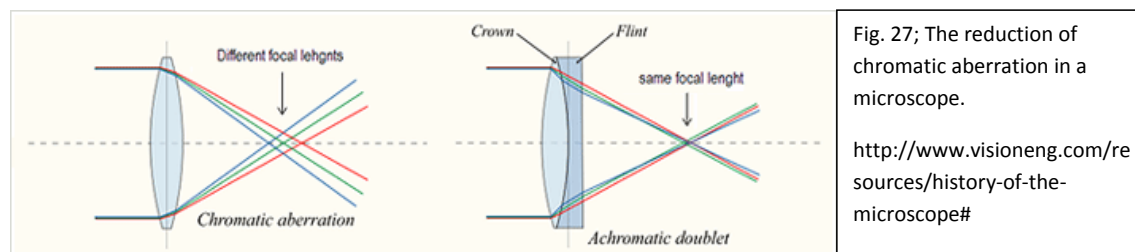


Fig. 27; The reduction of chromatic aberration in a microscope.

<http://www.visioneng.com/resources/history-of-the-microscope#>

The second problem was spherical aberration. This creates a blurry image due to the light rays not converging/diverging in the same place. This was resolved by Joseph Jackson Lister (~1830) by placing lenses particular distances from one another that would eliminate the aberration from all but the first lens. Also, it was found that if the first lens was a low power, low curvature lens the aberration problem was practically non-existent.

The third issue is that for a microscope to work optimally a large amount of light must be collected. This problem was worked out by Ernst Abbe (1870's) by determining the physical laws that control how the objective collects light and enhanced this by using water and oil immersion lenses. This provided Abbe with a resolution 10 xs greater than Leeuwenhoek. The resolution is about 200 nm which cannot be improved with an optical microscope due to the physical limitations of light's wavelength.

### Diffraction Limits:

The physical limits of light's wavelength cause resolution restrictions that are often referred to as the diffraction limit. This limit does not allow for an optical instrument to differentiate between two objects that have a separation distance that is about half the wavelength of light used on the specimen. Airy diffraction patterns are generated by light from two points passing through a circular aperture, such as the pupil of the eye. Points far apart (top) or meeting the Rayleigh criterion (middle) can be distinguished. Points closer than the Rayleigh criterion (bottom) are difficult to distinguish.

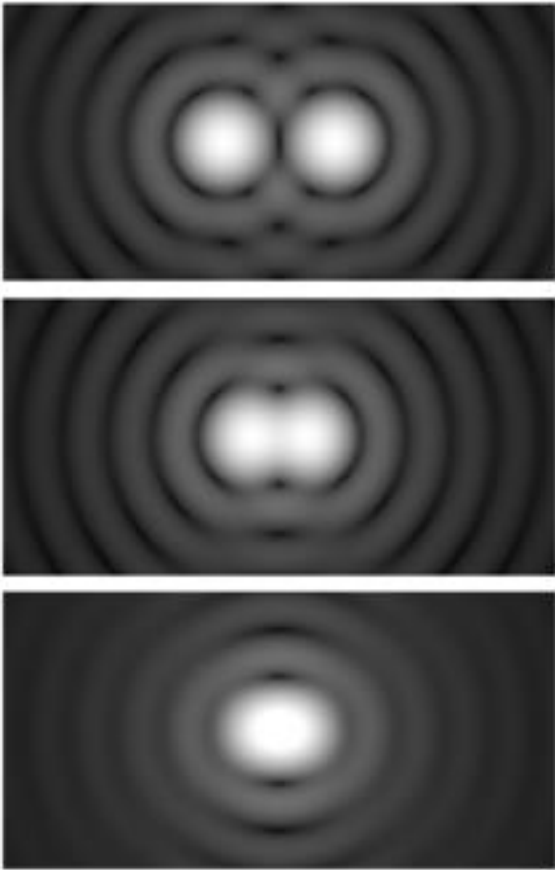


Fig. 28; Airy diffraction patterns

[http://en.wikipedia.org/wiki/Angular\\_resolution](http://en.wikipedia.org/wiki/Angular_resolution)

### Resolving Power:

The resolving power is the ability of an optical device to produce separate images of close specimens. The resolving power is greater with smaller wavelengths of light. There are a variety of microscope have different resolving powers. Light microscopes allow objects as small as a bacterium to be discerned. However, other microscopes such as Fluorescence, Super-resolution and Electron microscopes have much higher resolving power – the most powerful allow us to distinguish individual atoms.

The equation for resolving power is  $\sin \theta = 1.22\lambda/d$ .  $\theta$  = angular resolution,  $d$  = diameter of the lens' aperture,  $\lambda$  = wavelength of light.

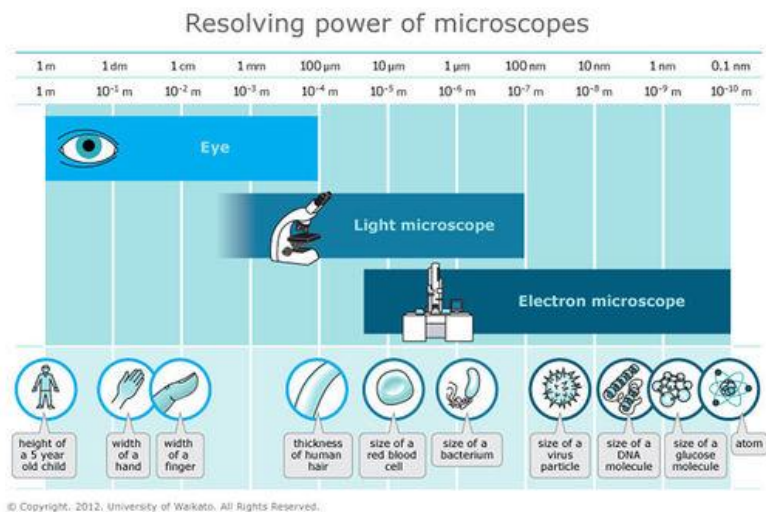


Fig. 29; resolving power of microscopes

<http://www.sciencelearn.org.nz/Contexts/Exploring-with-Microscopes/Sci-Media/Images/Resolving-power-of-microscopes>

### Fluorescence Microscopy:

The absorption and successive re-radiation of light by particular specimens is usually due to fluorescence or phosphorescence. The major distinction between these two processes is the time it takes the emitted light to decay. For fluorescence it is quite fast (milliseconds), whereas phosphorescence is slower and can take minutes up to hours to decay. The reason for the difference in decay time is due to the electron processes used.

In 1852, Sir George G. Stokes described fluorescence and coined the term when he noticed that the mineral fluor spar emitted red light when it was illuminated by UV light. He also observed that the fluorescence emission always happened at higher wavelengths than that of the excitation light. Throughout the 1800's studies were done on many different types of specimens that were shown to fluoresce when the objects had ultraviolet light shone upon them (ex: minerals, resins, crystals, chlorophyll, vitamins, etc.). Eventually in the 1930's scientist started to use fluorochromes to stain different specimens such as bacterium and portions of tissues. Often these stains were very specific to the particular light re-emitted.

Fluorescence microscopy has become an important tool in biological, medical and material sciences because of the characteristics that are not seen in traditional optical microscopes. Using fluorochromes allows for the identification of cells and cellular components with a great degree of specificity among the non-fluorescing material. Though fluorescence microscopy cannot resolve below the diffraction limit, the fluorescing molecules below this limit are readily detected. Some specimens show autofluorescence (without fluorochromes) but others must be stained with fluorochromes. These stains attach themselves to particular structures of the specimen which are excited by certain wavelengths of irradiating light and emitted light of specific intensities. One issue though with this technique is photobleaching. This is the fading of the fluorescent stain due to the exposure to light.

#### Photobleaching Rates in Multiply Stained Specimens

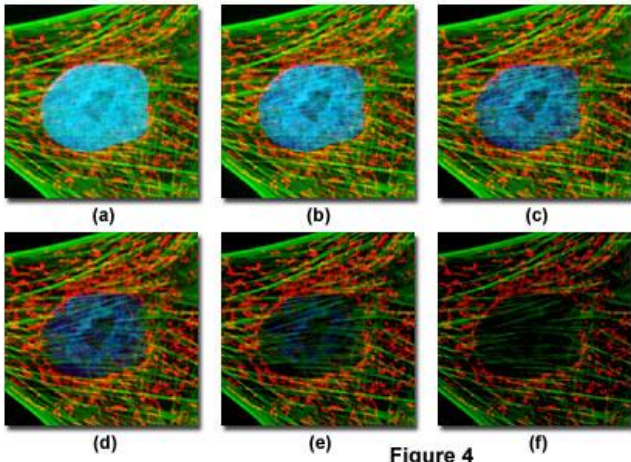


Figure 4

Fig. 30; Issues of fluorescence microscopy

<http://www.microscopyu.com/articles/fluorescence/fluorescenceintro.html>

#### Super-resolution Microscopy:

Though fluorescence microscopy provided certain advantages over traditional optical microscopy it is still burden with the diffraction limit of light and therefore can only collect so much information from standard objectives. Recently, there has been innovative approaches to by-pass the diffraction limit. These processes include near-field scanning optical microscopy (NSOM), structured illumination microscopy (SIM), stimulated emission depletion microscopy (STED) and reconstruction microscopy (STORM). Though these procedures have vastly improved the lateral (x-y) resolution down to tens of nanometers they each have their own limitations. These are only a few of the different types of super-resolution microscopes.

##### NSOM

Near-field scanning microscopy can produce super-resolution images by using the unique traits of evanescent waves and can create a resolution that is only limited by the physical size of the aperture (smaller than 20 nm). The refractive index, chemical structure, and fluorescence emission properties all contribute to the contrast.

##### SIM

Structured illumination (fluorescence) is a process that uses the moire' effect to gain finer spatial frequencies produced by light emissions from the specimen. These frequencies are produced from Fourier transforms by overlapping two different spatial frequencies from multiple directions. Software extracts the higher spatial frequency information from the specimen's produced moire' pattern. This results in a lateral resolution of about 100 nm and an axial (z) resolution close to 300 nm.

##### STED

Stimulated emission depletion microscopy uses high-intensity pulsed lasers that have unique modulation filters that control the excitation beam geometry. Though a lateral resolution of about 10 nm can be achieved these probes can possibly damage the specimen and require resistant photobleaching fluorescents. Also, the configurations of the microscope are very complex to assemble.

##### STORM

Stochastic optical reconstruction microscopy is based on the stochastic and sequential readout that has an exact localization of many single molecules from a specimen that were labeled with photoswitchable dyes with similar densities used in widefield and confocal fluorescence microscopy. An activation laser is used to cause emission switching so that any certain molecule has a small chance of being photoactivated, but most of the specimen remains in the dark emissive stage.

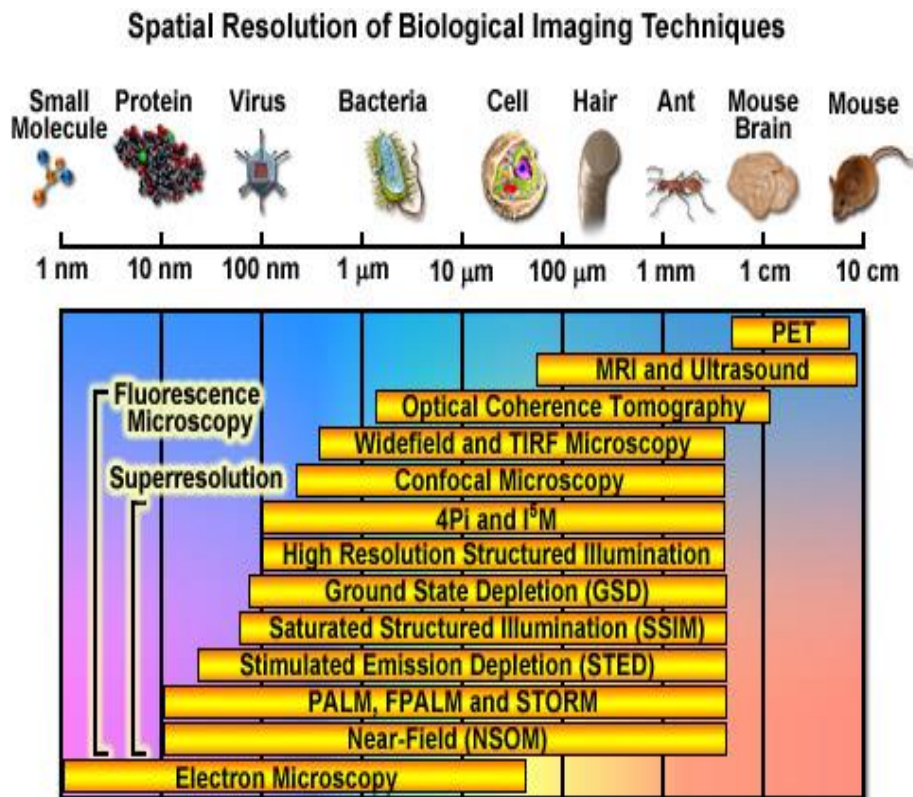


Fig. 31: Resolution of various types of microscopes

<http://zeiss-campus.magnet.fsu.edu/articles/superresolution/introduction.html>

## References:

### Books and Interviews:

- Serway, Raymond A., and Jerry S. Faughn. *Holt Physics*. Austin, Texas: Holt, Rinehart and Winston, 2000.
- Deeson, Eric.(2007). *Collins Internet-Linked Dictionary of Physics*. London: HarperCollins Publishers Ltd.
- Porter-Davis, Karen. Interview with Dr. Thomas Orlando. Department of Chemistry. Georgia Institute of Technology. Atlanta, Georgia. Summer 2013.

- Porter-Davis, Karen. Continuous interview with Giovanni DeLuca. Department of Chemistry. Georgia Institute of Technology. Atlanta, Georgia. Summer 2013.
- Porter-Davis, Karen. Interview with Dr. Jennifer Curtis. Department of Physics. Georgia Institute of Technology. Atlanta, Georgia. Summer 2014.
- Porter-Davis, Karen. Continuous interview with Dan Kovari. Department of Physics. Georgia Institute of Technology. Atlanta, Georgia. Summer 2014.

#### Websites:

- "FAQs: Embossed Holograms". *Viewholographics*. 2010. Web. 9 July 2013. < [http://www.viewholographics.com/faq/embossed\\_holograms](http://www.viewholographics.com/faq/embossed_holograms)>
- "Gem Notes: Gemological Spectroscopy". *Colored Gemstones. Suncoast Gem Lab*. 23 Jan 2013. Web. 9 July 2013. < <http://www.suncoastgemlab.com/blog/2013/01/gem-notes-gemological-spectroscopy/>>
- "History of the Microscope". *Vision Engineering*. n.p.n.d. pg. 1-7. Web. 16 July 2014. < <http://www.visioneng.com/resources/history-of-the-microscope#>>
- Helmenstine, Anne Marie. "Spectroscopy Introduction: Introduction to Spectroscopy and Types of Spectroscopy", *About.com Guide*. 2013. Web. 9 July 2013. <<http://chemistry.about.com/od/analyticalchemistry/a/spectroscopy.htm>>
- "Holography." *Encyclopædia Britannica. Encyclopædia Britannica Online*. Encyclopædia Britannica Inc., 2013. Web. 09 Jul. 2013. <<http://www.britannica.com/EBchecked/topic/269607/holography>>.
- "Holography", *Wikipedia* Wikimedia Foundation, Inc. 27 June 2013 Web. 2 July 2013. < <http://en.wikipedia.org/wiki/Holography>>
- "How Lasers Work", National Ignition Facility. National Nuclear Security Administration. *Lawrence Livermore National Laboratory*. Web. 2 July 2013. < [https://lasers.llnl.gov/education/how\\_lasers\\_work.php](https://lasers.llnl.gov/education/how_lasers_work.php)>
- "Introduction to Spectroscopy", NASA's Imagine the Universe; *High Energy Astrophysics Science Archive Research Center*. 05 Sep 2006. Web. 02 July 2013. [http://imagine.gsfc.nasa.gov/docs/teachers/lessons/xray\\_spectra/background-spectroscopy.html](http://imagine.gsfc.nasa.gov/docs/teachers/lessons/xray_spectra/background-spectroscopy.html)
- "Introduction to Super resolution Microscopy". *Education in Microscopy and Digital Imaging*. Carl Zeiss and Molecular Expressions. Web. 06 June 2014 <http://zeiss-campus.magnet.fsu.edu/articles/superresolution/introduction.html>
- Kulesa, Craig. "What is Spectroscopy", *Arizona State University*. 4 Feb 1997. Web. 3 July 2013. < [http://loke.as.arizona.edu/~ckulesa/camp/spectroscopy\\_intro.html](http://loke.as.arizona.edu/~ckulesa/camp/spectroscopy_intro.html)>
- "Laser", *Wikipedia* Wikimedia Foundation, Inc. 2 July 2013 Web. 2 July 2013. < <http://en.wikipedia.org/wiki/Laser>>
- "Raman Spectroscopy" *Wikipedia* Wikimedia Foundation, Inc. 23 June 2013 Web. 2 July 2013. <[http://en.wikipedia.org/wiki/Raman\\_spectroscopy](http://en.wikipedia.org/wiki/Raman_spectroscopy)>

- “Raman Spectroscopy: Tutorial”, Laboratory of Photo-induced Effects Vibrational and X-ray Spectroscopies. *Physics Department, University of Parma*. 2007 Web. 2 July 2013.  
[http://www.fis.unipr.it/phevix/raman\\_tutorial.html](http://www.fis.unipr.it/phevix/raman_tutorial.html)
- “Reflection Holograms”. HyperPhysics. *Department of Physics and Astronomy: Georgia State University*. 2012. Web. 9 July 2013. < <http://hyperphysics.phy-astr.gsu.edu/hbase/optmod/holog3.html>>
- Reusch, William. “Infrared Spectroscopy”, *Department of Chemistry: Michigan State University*. 5 May 2013. Web. 9 July 2013.  
<<http://www2.chemistry.msu.edu/faculty/reusch/VirtTxtJml/Spectrpy/InfraRed/infrared.htm#ir1>>
- Silfies, Joel S.; Schwartz, Stanley A.; Davidson, Michael W. “The Diffraction Barrier in Optical Microscopy”, *Microscopy U: Nikon*. Copyright 2000-2013. Web. 16 July 2014.  
<http://www.microscopyu.com/articles/superresolution/diffractionbarrier.html>
- Silfies, Joel S.; Schwartz, Stanley A.; Martini, Sunita; Price, Stephen P.; Coker, Alex B.; Davidson, Michael W. “Fundamental Concepts in Super-resolution Microscopy”, *Microscopy U: Nikon*. Copyright 2000-2013. Web. 16 July 2014. <http://www.microscopyu.com/articles/superresolution/index.html>
- Smith, Steven W. Ph.D. *The Scientist and Engineer's Guide to Digital Signal Processing* © 1997-2011 by California Technical Publishing. Web. 06 June 2014. <http://www.dspguide.com/copyrite.htm>
- Spring, Kenneth R.; Davidson, Michael W. “Introduction Fluorescence Microscopy”, *Microscopy U: Nikon*. Copyright 2000-2013. Web. 16 July 2014.  
<http://www.microscopyu.com/articles/fluorescence/fluorescenceintro.html>
- “Transmission Holograms”. Viewholographics. nd. Web. 2 July 2013.<  
[http://viewholographic.com/holograms/transmission\\_holograms](http://viewholographic.com/holograms/transmission_holograms)>
- Wright, Edward L. “Spectroscopy and Astronomy”, *UCLA*. 28 Aug 1999. Web. 9 July 2013.  
<<http://www.astro.ucla.edu/~wright/fluxplot.html>>

# INTERFERENCE AND DIFFRACTION DEMONSTRATIONS

## **Diffraction Grating Demonstration:**

Take the red laser pointer and shine it through a diffraction grating on the wall/white board in a darkened room. Have the students attempt to explain what is occurring with the laser light. Have a student come up to the wall and point out the central bright fringe. Have them mark off the bright fringes with a marker (or if on a wall you can have them use red stickers – like Avery color coding labels). Then bring out the green laser and ask the students to predict how the green laser will diffract compared to the red laser (remind them about the wavelength size difference between red and green). Repeat the previous procedure with the green laser and have the student mark off the bright fringes (make sure you are pointing it in the same direction at the same level. After they are marked off turn on the lights and compare and discuss how the diffraction of light differs depending on wavelength.

## **Spectroscope Demonstration:**

Pass out diffraction gratings and spectroscopes to each student or pairs of students. REMIND THE STUDENTS NOT TO TOUCH THE GRATING PART OF THE SLIDE. If you do not have any spectroscopes the diffraction gratings will do. As a class have the students look through the diffraction gratings and spectroscopes at different light sources (NOT THE SUN). It is best if you have several different sources like an emission box with neon, hydrogen and helium gas, but also incandescent, halogen and fluorescent sources. Open up a discussion of what students are seeing and if the sources of light all look the same and why they look different. Also, if you are using both diffraction gratings and spectroscopes have the students explain the similarities and differences (both split the light into a spectrum, but a spectroscope usually will provide a scale to measure the wavelength of the bands – also since spectroscopes have the grating enclosed it can be easier to see the spectra). If you are just using diffraction gratings, below are tips on how to help the students see the spectra.

- a) Darken the room.
- b) Hold the grating close to the eye and look through it at a light source.
- c) Make sure that the gratings are turned so the grooves run vertically.
- d) Look off to either side of the light source. This may take some practice.
- e) If they are having problems seeing the spectra they may need to try holding grating different distances from their eye and/or closing the eye not in front of the grating.

# **INTRODUCTION TO THE INTERFERENCE AND DIFFRACTION OF LIGHT WORKSHEET**

**Name:** \_\_\_\_\_ **Date:** \_\_\_\_\_ **Period:** \_\_\_\_\_

- 1. Does interference of light only occur with visible light? If not, give an example.**
- 2. Explain why light has a dual nature. Use examples to support your answer.**
- 3. What results when visible light has constructive and destructive interference?**
- 4. Define coherence.**
- 5. What is a spectrometer? Name at least two uses.**

**6. What is the difference between transmission and reflective diffraction gratings?**

**7. What is necessary for an optical instrument to have high resolution or resolving power?**

**8. Which object would produce the most distinct diffraction pattern: your textbook, your house key or a strand of your hair? Explain why.**

**9. Would red or green light produce a wider diffraction pattern? Explain why.**

**10. What does the acronym, laser, mean? How does a laser differ from incandescent light (name at least three ways)? Name two uses for lasers.**

# INTRODUCTION TO THE INTERFERENCE AND DIFFRACTION OF LIGHT WORKSHEET

## Teacher copy

Name: \_\_\_\_\_ Date: \_\_\_\_\_ Period: \_\_\_\_\_

1. Does interference of light only occur with visible light? If not, give an example.

No, interference can occur with all electromagnetic waves. One common example is with radio waves (affects cell phones, radios, television, etc.). X-rays are also good examples.

2. Explain why light has a dual nature. Use examples to support your answer.

This means that light can act as a wave but also as a particle (photon). The way light diffracts demonstrates wave characteristics (Huygens, Fresnel or Young's experiments), but the photo electric effect (other ex: Compton's or J.J. Thomsons' experiment can also be used) demonstrated how light can act as a particle as well.

3. What results when visible light has constructive and destructive interference?

For constructive interference the light waves will combine and produce bright fringes and with destructive interference the light waves will cancel (or reduce) to produce dark/dim fringes.

4. Define coherence.

The property by which two waves with identical wavelengths maintain a constant phase relationship. (Holt Physics book definition)

5. What is a spectrometer? Name at least two uses.

A spectrometer is a simple device that uses a diffraction grating to separate the light from a source into its monochromatic components. All elements have their

own unique “fingerprint” and so spectrometers are used in astronomy to determine the make-up and temperatures of stars and galaxies, in gemology to establish the composition of gems and stones, and in chemistry to ascertain the chemical structure and make-up of chemical compounds and solutions.

**6. What is the difference between transmission and reflective diffraction gratings?**

A transmission grating is made of a transparent substance, so that the diffracted light goes through the grating and displays the pattern on the other side of the object. A reflection grating is made of a reflective/opaque substance; so the diffracted light bounces off and creates a pattern on the same side.

**7. What is necessary for an optical instrument to have high resolution or resolving power?**

The angle between the resolved objects should be as small as possible. The shorter the wavelength of the incident light or the wider the aperture (opening through which light passes) the smaller the angle of resolution and the greater the resolving power will be. The limiting angle of resolution in radians for an optical instrument with a circular aperture is  $\theta = 1.22 \lambda/D$

**8. Which object would produce the most distinct diffraction pattern: your textbook, your house key or a strand of your hair? Explain why.**

**Your strand of hair. Its size is nearest the size of the wavelength of visible light.**

**9. Would red or green light produce a wider diffraction pattern? Explain why.**

**Red light; Longer wavelengths are diffracted more.**

**10. What does the acronym, laser, mean? How does a laser differ from incandescent light (name at least three ways)? Name two uses for lasers.**

**Light Amplification by Stimulated Emission of Radiation; Lasers are monochromatic, directional and coherent unlike incandescent light. Bar codes, surgeries, optical tweezers, determining distances, CD/DVD players, scientific research, etc.**

# INTERFERENCE AND DIFFRACTION PROBLEMS

Name: \_\_\_\_\_ Date: \_\_\_\_\_ Period: \_\_\_\_\_

**Constructive Interference:**  $d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots$

**Destructive Interference:**  $d(\sin\theta) = (m + \frac{1}{2})\lambda$   $m = 0, \pm 1, \pm 2, \dots$

**Diffraction:**  $d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots$

1. Light from a Helium-Neon laser falls on a double slit with a slit separation of  $2.03 \times 10^{-6}$  m, and the first bright fringe is seen at an angle of  $18.16^\circ$  relative to the central maximum. Determine the wavelength of the light source.
2. If the distance between two slits is  $3.33 \times 10^{-3}$  mm, determine the angle between the first-order and second-order bright fringes for the yellow spectra of a sodium lamp with a wavelength of 589 nm.
3. A pair of narrow parallel slits are illuminated by the blue component of a mercury vapor lamp with a wavelength of 435.8 nm. The angle from the central maximum to the first bright fringe is  $16.2^\circ$ . Determine the distance between the slits.
4. The distance between slits in a double-slit interference experiment is 0.055 mm. The second-order bright fringe is measured to have an angle of  $3.45^\circ$  from the central maximum. Calculate the wavelength of the light source.

5. Light with a wavelength of 574 nm falls on a double slit interference experiment ( $d = 2.5$  mm). Calculate the angle between the central maximum and the second dark fringe.
6. Convert the following into  $d$  (distance between slits):
- a. 300,000 lines/m
  - b. 2150 lines/cm
  - c. 428 lines/mm
7. Light from a Krypton laser ( $\lambda = 416$  nm) shines on a diffraction grating with 175,000 lines/m. Solve for the angle between the central maximum and the first-order maximum.
8. A grating with 1525 lines/cm is illuminated with light of wavelength 632.8 nm. What is the angle between the central maximum and the second-order maximum?
9. A diffraction grating has blue light with a wavelength of 475 nm shone on it. An angle of  $11^\circ$  is determined between the central maximum and first-order maximum. What is the distance between the slits?
10. Light from a Nitrogen laser ( $\lambda = 337.1$  nm) shines on the surface of a diffraction grating that has 525 lines/mm. Determine the angles at which you would observe the first and second order maxima.

# INTERFERENCE AND DIFFRACTION PROBLEMS

## TEACHER'S COPY

Name: \_\_\_\_\_ Date: \_\_\_\_\_ Period: \_\_\_\_\_

**Constructive Interference:**  $d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots$

**Destructive Interference:**  $d(\sin\theta) = (m + \frac{1}{2})\lambda$   $m = 0, \pm 1, \pm 2, \dots$

**Diffraction:**  $d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots$

1. Light from a Helium-Neon laser falls on a double slit with a slit separation of  $2.03 \text{ E} - 6 \text{ m}$ , and the first bright fringe is seen at an angle of  $18.16^\circ$  relative to the central maximum. Determine the wavelength of the light source.

$$d(\sin\theta) = m\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow \lambda = d(\sin\theta)/m \rightarrow \lambda = (2.03 \text{ E} - 6)(\sin 18.16^\circ)/1 \rightarrow$$

$$\underline{6.327 \text{ E} - 7 \text{ m or } 632.7 \text{ nm}}$$

2. If the distance between two slits is  $3.33 \text{ E} - 3 \text{ mm}$ , determine the angle between the first-order and second-order bright fringes for the yellow spectra of a sodium lamp with a wavelength of  $589 \text{ nm}$ .

$$\text{Convert: } 3.33 \text{ E} - 3 \text{ mm} \rightarrow 3.33 \text{ E} - 6 \text{ m and } 589 \text{ nm} \rightarrow 589 \text{ E} - 9 \text{ m or } 5.89 \text{ E} - 7 \text{ m}$$

$$\underline{1^{\text{st}} \text{ order:}} \quad d(\sin\theta) = m\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow \theta = \sin^{-1}(m\lambda/d) \rightarrow \theta = \sin^{-1}([(1)(589 \text{ E} - 9)]/(3.33 \text{ E} - 6))$$

$$\underline{10.19^\circ}$$

$$\underline{2^{\text{nd}} \text{ order:}} \quad d(\sin\theta) = m\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow \theta = \sin^{-1}(m\lambda/d) \rightarrow \theta = \sin^{-1}([(2)(589 \text{ E} - 9)]/(3.33 \text{ E} - 6))$$

$$\underline{20.72^\circ}$$

3. A pair of narrow parallel slits are illuminated by the blue component of a mercury vapor lamp with a wavelength of  $435.8 \text{ nm}$ . The angle from the central maximum to the first bright fringe is  $16.2^\circ$ . Determine the distance between the slits.

$$\text{Convert: } 435.8 \text{ nm} \rightarrow 435.8 \text{ E} - 9 \text{ m or } 4.358 \text{ E} - 7 \text{ m}$$

$$d(\sin\theta) = m\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow d = m\lambda/\sin\theta \rightarrow d = [(1)(435.8 \text{ E} - 9)]/\sin 16.2^\circ \rightarrow \underline{1.56 \text{ E} - 6 \text{ m}}$$

4. The distance between slits in a double-slit interference experiment is  $0.055 \text{ mm}$ . The second-order bright fringe is measured to have an angle of  $0.75^\circ$  from the central maximum. Calculate the wavelength of the light source.

$$\text{Convert: } 0.055 \text{ mm} \rightarrow 5.5 \text{ E} - 5 \text{ m}$$

$$d(\sin\theta) = m\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow \lambda = d(\sin\theta)/m \rightarrow \lambda = (5.5 \text{ E} - 5)(\sin 0.75^\circ)/2 \rightarrow$$

$$\underline{359.96 \text{ E} - 7 \text{ m}}$$

5. Light with a wavelength of 574 nm falls on a double slit interference experiment ( $d = 0.25 \text{ mm}$ ). Calculate the angle between the central maximum and the second dark fringe.

**Convert:  $574 \text{ nm} \rightarrow 574 \text{ E } -9 \text{ m}$  or  $5.74 \text{ E } -7 \text{ m}$  and  $0.25 \text{ mm} \rightarrow 2.5 \text{ E } -4 \text{ m}$**

**Remember the 2<sup>nd</sup> dark fringe is between the 1<sup>st</sup> and 2<sup>nd</sup> bright fringe so  $m = 1$**

$$d(\sin\theta) = (m + \frac{1}{2})\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow \theta = \sin^{-1}([(m + \frac{1}{2})\lambda]/d) \rightarrow \theta = \sin^{-1}([(1 + \frac{1}{2})(574 \text{ E } -9)]/(2.5 \text{ E } -4)) \rightarrow$$

**0.197°**

6. Convert the following into  $d$  (distance between slits) in meters:

a.  $300,000 \text{ lines/m} \rightarrow (300,000)^{-1} \rightarrow \underline{3.33 \text{ E } -6 \text{ m}}$

b.  $2150 \text{ lines/cm} \rightarrow (2150)^{-1} \rightarrow 4.65 \text{ E } -4 \text{ cm} \rightarrow \underline{4.65 \text{ E } -6 \text{ m}}$

c.  $428 \text{ lines/mm} \rightarrow (428)^{-1} \rightarrow 2.34 \text{ E } -3 \text{ mm} \rightarrow \underline{2.34 \text{ E } -6 \text{ m}}$

7. Light from a Krypton laser ( $\lambda = 416 \text{ nm}$ ) shines on a diffraction grating with 175,000 lines/m. Solve for the angle between the central maximum and the first-order maximum.

**Convert:  $416 \text{ nm} \rightarrow 416 \text{ E } -9 \text{ m}$  or  $4.16 \text{ E } -7 \text{ m}$  and  $175,000 \text{ lines/m} \rightarrow 5.71 \text{ E } -6 \text{ m}$**

$$d(\sin\theta) = m\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow \theta = \sin^{-1}(m\lambda/d) \rightarrow \theta = \sin^{-1}([(1)(416 \text{ E } -9)]/(5.71 \text{ E } -6)) \rightarrow$$

**4.18°**

8. A grating with 1525 lines/cm is illuminated with light of wavelength 632.8 nm. What is the angle between the central maximum and the second-order maximum?

**Convert:  $1525 \text{ lines/cm} \rightarrow 6.56 \text{ E } -4 \text{ cm} \rightarrow 6.56 \text{ E } -6 \text{ m}$  and  $632.8 \text{ nm} \rightarrow 632.8 \text{ E } -9 \text{ m}$  or  $6.328 \text{ E } -7 \text{ m}$**

$$d(\sin\theta) = m\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow \theta = \sin^{-1}(m\lambda/d) \rightarrow \theta = \sin^{-1}([(2)(632.8 \text{ E } -9)]/(6.56 \text{ E } -6))$$

**11.12°**

9. A diffraction grating has blue light with a wavelength of 475 nm shone on it. An angle of 11° is determined between the central maximum and first-order maximum. What is the distance between the slits?

**Convert:  $475 \text{ nm} \rightarrow 475 \text{ E } -9 \text{ m}$  or  $4.75 \text{ E } -7 \text{ m}$**

$$d(\sin\theta) = m\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow d = m\lambda/\sin\theta \rightarrow d = [(1)(475 \text{ E } -9)]/\sin 11^\circ \rightarrow \underline{2.49 \text{ E } -6 \text{ m}}$$

10. Light from a Nitrogen laser ( $\lambda = 337.1 \text{ nm}$ ) shines on the surface of a diffraction grating that has 525 lines/mm. Determine the angle at which you would observe at the second order maximum.

**Convert:  $337.1 \text{ nm} \rightarrow 337.1 \text{ E } -9 \text{ m}$  or  $3.371 \text{ E } -7 \text{ m}$  and  $525 \text{ lines/mm} \rightarrow 1.905 \text{ E } -3 \text{ mm} \rightarrow 1.905 \text{ E } -6 \text{ m}$**

$$d(\sin\theta) = m\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow \theta = \sin^{-1}(m\lambda/d) \rightarrow \theta = \sin^{-1}([(2)(337.1 \text{ E } -9)]/(1.905 \text{ E } -6))$$

**20.73°**

# DIFFRACTION GRATING LAB

**MATERIALS:**

Diffraction gratings, a CD/DVD with aluminum coating removed, laser pointer, ring-stand with clamp, and white screen (or poster board)

**PROCEDURE:**

Use the information on the diffraction gratings to compare the calculated angle of diffraction with the measured one (first order maximum). Use a CD/DVD as a diffraction grating and determine the distance between the grooves.

**DATA:**

DIFFRACTION EQUATIONS

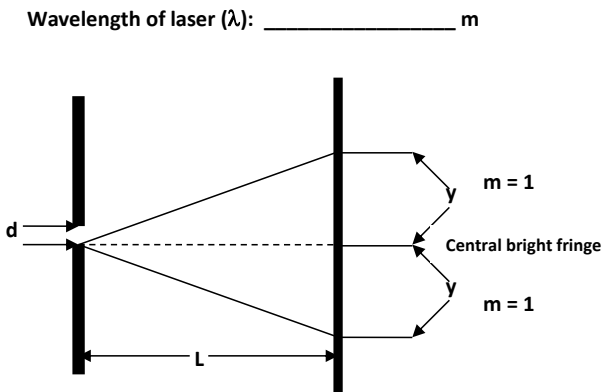
$$d \sin \theta_{\text{calc.}} = m \lambda \quad \text{and} \quad y = L \tan \theta_{\text{observed}}$$

$d$  = distance between slits

$\theta$  = path angle

$m$  = order number

$\lambda$  = wavelength of light



Grating	d (meters)	y (meters)	L (meters)	$\theta_{\text{calculated}}$	$\theta_{\text{observed}}$	% Error
100 lines/mm						
300 lines/mm						
530 lines/mm						

Formatted Table

600 lines/mm						
--------------	--	--	--	--	--	--

**For the CD/DVD:**

Calculate the  $\theta_{\text{diffraction}}$  for the first order maximum using the measured  $y$  and  $L$ . Then using the calculated angle solve for  $d$  using  $d\sin\theta_{\text{calc.}} = m\lambda$ . Compare it to the  $d$  measured from the AFM image of the CD/DVD using the % Error equation.

y (meters)	L (meters)	$\theta_{\text{diffraction}}$	$d_{\text{calculated}}$ (meters)	$d_{\text{measured}}$ (meters)	% Error

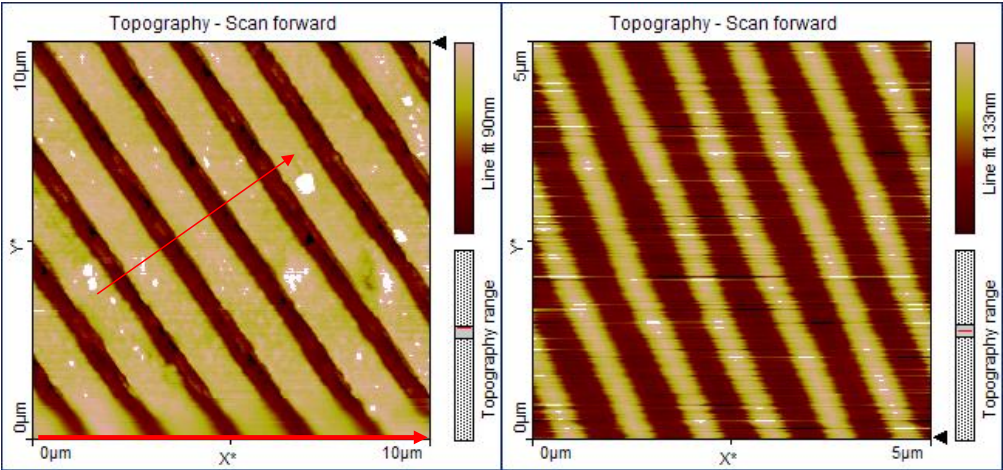


Fig1a. AFM image : Sample : Memorex CD 750 MB; blank; scan size 10 micrometer      2a. AFM image Sample : Sony DVD-R 4.7 GB; Blank, scan size 5.0 micrometer

# MICROSCOPE INTERNET SCAVENGER HUNT

1. What is a main concern in optical microscope resolution? Explain.
2. What is the Rayleigh Criterion?
3. What are airy disks? How do they change with wavelength and aperture size? Whom were they named after?
4. How many lenses are used in an optical compound microscope? What are they? What type of lenses are they, convex or concave?
5. How do you calculate the total magnification of an optical compound microscope?

# MICROSCOPE INTERNET

## SCAVENGER HUNT **TEACHER COPY**

1. What is a main concern in optical microscope resolution? Explain.

**The Diffraction Resolution Limit. This resolution is defined as the shortest distance between two points on a specimen that can still be distinguished by the observer or camera system as separate entities.**

2. What is the Rayleigh Criterion?

**Generally accepted criterion for the minimum resolvable detail – the imaging process is said to be diffraction-limited when the first diffraction min of the image of one source point coincides with the max of another.**

3. What are airy disks? How do they change with wavelength and aperture size? Whom were they named after?

**The bright central spot of the pattern produced by light diffracted when passing through a small circular aperture. As wavelength decreases the airy disks decreases; As the aperture decreases the airy disks increase; British Astronomer: George Biddell Airy**

4. How many lenses are used in an optical compound microscope? What are they? What type of lenses are they, convex or concave?

**Three to four main lenses: eyepiece, condenser, objective (projector lens); convex lenses**

5. How do you calculate the total magnification of an optical compound microscope?

**Eyepiece (~10 x) x mag of objective ocular lens**

# INTERFERENCE AND DIFFRACTION REVIEW PROJECT

## Instructions:

You are to create a Flash Chart (A heavy-duty paper notebook insert) or Poster as a review guide for Refraction, Lenses and Optical Phenomenon. This project will be due on \_\_\_\_\_. There will be a 10 pt deduction for every school day the project is late without proper excuse.

## The Flash Chart/Poster should include:

- a) A title and a brief overview of the entire unit.
- b) Divisions for each section (three sections: Interference, Diffraction and Lasers) in the unit.
- c) Each section division should include:
  - 1) The section objectives (summary)
  - 2) All important terms and their definitions
  - 3) All equations used in the section with example problems for each
  - 4) At least two visuals (charts, graphs, diagrams, pictures, etc.) that relate to the section.
- d) All Flash Charts should be typed (only exception – the calculations) and placed on colored paper (no notebook paper). Posters can be designed on poster board or through the website <http://edu.glogster.com> . Content quality, readability (organization), neatness and creativity will all be considered.

# FLASH CHART RUBRIC

Name: \_\_\_\_\_ Date: \_\_\_\_\_ Period: \_\_\_\_\_

	0	2	3	5	
<b>TITLE OF CHAPTER/TOPIC</b>	No Title	Non-Relevant Title	Appropriate Title Given with Grammatical Errors	Appropriate Title Given	
	0-3	4-6	8	10	
<b>SYNOPSIS OF CHAPTER/TOPIC</b>	Requirement not Met/Very Unorganized with Grammatical Errors	Unorganized with/without Grammatical Errors	Clear, Concise Synopsis with a few Grammatical Errors	Clear, Concise Synopsis with no Grammatical Errors	
	0 - 6	8 - 12	14 -18	20	
<b>SECTION OBJECTIVES</b>	Requirement not Met/Less than 50% of Section Objectives Answered Correctly	50 – 74% of Section Objectives Answered Correctly	At least 75 % of Section Objectives Answered Correctly	All Section Objectives Answered Correctly	
	0 - 3	4 - 6	7 - 9	10	
<b>IMPORTANT TERMS</b>	Requirement not Met/Less than 50% of Terms Defined Correctly	50 – 74% of Terms Defined Correctly	At least 75 % Terms Defined Correctly	All Terms Defined Correctly	
	0 - 3	4 - 6	7 - 9	10	
<b>EQUATIONS</b>	Requirement not Met/Less than 50% of Equations Defined Correctly	50 – 74% of Equations Defined Correctly	At least 75 % Equations Defined Correctly	All Equations Defined Correctly	

	<b>0 - 3</b>	<b>4 - 5</b>	<b>7 - 8</b>	<b>10</b>	
<b>SECTION VISUALS</b>	<b>Missing More than 4 Meaningful Visuals</b>	<b>Missing 3-4 Meaningful Visuals</b>	<b>Missing 1-2 Meaningful Visuals</b>	<b>At least Two Meaningful Visuals for Each Section</b>	
	<b>0 - 3</b>	<b>4 - 6</b>	<b>8</b>	<b>10</b>	
<b>TYPED FLASH CHARTS</b>	<b>Requirement not Met/Less than 75% of Flash Chart is Typed (sans calculation)</b>	<b>At least 75 % of Flash Chart is Typed (sans calculations)</b>	<b>All of the Flash Chart is Typed (messy calculations)</b>	<b>All of the Flash Chart is Typed (sans calculations but they are written neatly)</b>	
	<b>4</b>	<b>6</b>	<b>8</b>	<b>10</b>	
<b>CONTENT QUALITY</b>	<b>Content Quality is Poor</b>	<b>Content Quality is Satisfactory</b>	<b>Content Quality is Very Good</b>	<b>Content Quality is Excellent</b>	
	<b>4</b>	<b>6</b>	<b>8</b>	<b>10</b>	
<b>ORGANIZATION/ NEATNESS</b>	<b>Majority of Flash Chart is Unorganized</b>	<b>Some Sections of the Flash Chart are Unorganized</b>	<b>Flash Chart is Organized</b>	<b>Flash Chart is Very Organized</b>	
	<b>1</b>	<b>2</b>	<b>3</b>	<b>5</b>	
<b>CREATIVITY/ PERCEIVED EFFORT</b>	<b>Very Little Perceived Effort</b>	<b>Some Perceived Effort</b>	<b>Creative Touches Were Added/ Some Perceived Effort</b>	<b>Meaningful Creative Touches Were Added/ A lot of Perceived Effort</b>	

**Bonus Points:** \_\_\_\_\_

**Total Score:** \_\_\_\_\_

RUBRIC FOR POSTER/BROCHURE/VIDEO/COMIC BOOK

Name(s): Project: Period(s):

CRITERIA					POINTS
	0-11	12-17	18-23	24-30	
QUALITY OF INFORMATION	Information does not relate to the task and is difficult to follow.	Information is somewhat related to the task.	Information presented is relative to task and information is somewhat easy to understand.	Information presented is very relative to task and information is very easy to understand.	
	0-11	12-17	18-23	24-30	
VISUAL NEATNESS AND ORGANIZATION	Project is very messy and unorganized. Very little effort is perceived.	Project is a little messy and/or unorganized. Some effort is perceived.	Project is fairly neat and organized. A good amount of effort is perceived.	Project is very neat and organized. A great deal of effort is perceived.	
	0-3	4-9	10-15	16-20	
CREATIVITY	Project shows no creative thought in presentation.	Project displays some creative thought.	Project is creative and relevant to the task. (Creative Flare)	Very creative and relevant to the task. A very unique presentation.	
	0-4	5-7	8	10	
TECHNICAL ASPECTS (GRAMMAR/SPELLING, ETC.)	Many technical mistakes (more than three).	Two to three technical mistakes.	One technical mistake.	No technical mistakes.	
	0	4-7	8	10	
REFERENCES	No references	Some type of reference and documentation.	At least two quality references.	At least two quality references documented correctly.	

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Total Points: /100

Teacher Comments:

# TEAM TRIVIA: INTERFERENCE AND DIFFRACTION

**Instructions:** Divide class into groups of 3 or 4. Pass out 4 note cards (with letters A, B, C, and D on one card each) to each group OR if you have a clicker system with your Smartboard give each group a remote (there is a ppt with these questions on them). Allow students to use scrap paper and calculators. You may provide equations to each group as well. Read the question and all the choices allowed to the class and let each group send up a representative with their answer. Every group should get a chance to answer (this is not a first come first served game). At the end of the multiple choice round pass out the Bonus Round Sheet to each group to work on (you may establish an appropriate time limit). Tally up each groups' points. I usually give 1<sup>st</sup> place 6 pts on their evaluation, 2<sup>nd</sup> place 5 pts, etc. (you can award your winners any way that you like).

1. Projected on a screen is a two-slit interference pattern, the fringes are evenly spaced on the screen

- a) Only for small angles
- b) Only for large angles
- c) Only at 45°
- d) never

2. Which of the following is a monochromatic and coherent light source?

- a) LED
- b) Fluorescent
- c) Laser
- d) Incandescent

3. Which is not a type of hologram that was discussed?

- a) refraction
- b) transmission
- c) pulsed
- d) embossed

4. What is the function of a spectrometer?

- a) To eliminate light dispersion
- b) To reduce constructive interference
- c) To separate light from a source into its monochromatic components
- d) To produce coherent light

5. All lasers use a substance called the \_\_\_\_\_ to which energy is added to produce coherent light.
- a) Gas-ion barrier
  - b) Stimulated emission
  - c) Photon beam
  - d) Active medium
6. Instruments that have high resolution are created to
- a) Reduce interference
  - b) Eliminate coherence of light waves
  - c) Enhance dispersion
  - d) Maximize diffraction patterns
7. In a double slit experiment, the angle between the central maximum and the second bright fringe is  $2^\circ$ . The slit separation is  $3.8 \times 10^{-5} \text{ m}$ . What is the wavelength of the light source?
- a)  $5.3 \times 10^{-7} \text{ m}$
  - b)  $6.6 \times 10^{-7} \text{ m}$
  - c)  $5.9 \times 10^{-8} \text{ m}$
  - d)  $6.4 \times 10^{-8} \text{ m}$
8. To meet the needs to form an interference pattern a(n) \_\_\_\_\_ is usually used as a light source.
- a) Halogen bulb
  - b) Mercury vapor lamp
  - c) Laser
  - d) Light Emitting Diode
9. Which of the following changes would increase the resolution of a telescope?
- a) Observing light at a low wavelength, increasing the aperture
  - b) Observing light at a low wavelength, decreasing the aperture
  - c) Observing light at a high wavelength, increasing the aperture
  - d) Observing light at a high wavelength, decreasing the aperture
10. Extra point question: The inelastic scattering (KE is not conserved) of a photon is called
- a) Rayleigh Scattering
  - b) Tyndall Scattering
  - c) Raman Scattering
  - d) Mie Scattering

# INTERFERENCE AND DIFFRACTION

## BONUS ROUND

Group Member Names: \_\_\_\_\_ Date: \_\_\_\_\_ Period: \_\_\_\_\_

Group #: \_\_\_\_\_

1. If you had two incandescent light bulbs as your light source would interference occur? Explain your answer.
2. Who first demonstrated interference in light waves from two sources in 1801?
3. In a double slit interference pattern the 1<sup>st</sup> order bright fringe appears 0.25 cm from the central maximum. The distance between the slits is 0.5 mm and the wavelength is 463 nm. What is the angle?
4. The colors formed on a soap bubble are caused mainly by \_\_\_\_\_.
5. Why is blue light used for illumination in an optical microscope?
6. In a double slit experiment the slits are separated by 0.3096 mm and has a light with a wavelength of 589 nm. What is the angle of the 4<sup>th</sup> order minimum from the central maximum?

# ANSWER KEY: INTERFERENCE AND DIFFRACTION BONUS ROUND

Group Member Names: \_\_\_\_\_ Date: \_\_\_\_\_ Period: \_\_\_\_\_

Group #: \_\_\_\_\_

1. If you had two incandescent light bulbs as your light source would interference occur? Explain your answer.

No interference occurs. The sources must be coherent (maintain a constant phase change with respect to each other) and light waves from an ordinary source such as a light bulb undergo random phase changes in time intervals shorter than a nanosecond that our eyes cannot follow such rapid changes and therefore no interference is observed. Also, the source should be monochromatic (single wavelength). \*You can create a set-up that makes the light bulbs coherent.

2. Who first demonstrated interference in light waves from two sources in 1801?

Thomas Young

3. In a double slit interference pattern the 1<sup>st</sup> order bright fringe appears 0.25 cm from the central maximum. The distance between the slits is 0.5 mm and the wavelength is 463 nm. What is the angle?

Convert: 0.25 cm  $\rightarrow$  2.5 E -3 m, 0.5 mm (not needed to solve problem)  $\rightarrow$  5 E -4 m, and 463 nm  $\rightarrow$  463 E -9 m or 4.63 E -7 m

$$d(\sin\theta) = m\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow \theta = \sin^{-1}(m\lambda/d) \rightarrow \theta = \sin^{-1}([(1)(463 \text{ E } -9)]/(5 \text{ E } -4)) = \underline{0.05^\circ}$$

4. The colors formed on a soap bubble are caused mainly by \_\_\_\_\_.

Interference patterns (reflection and refraction do occur in soap bubbles but the colors are formed because different wavelengths interfere)

5. Why is blue light used for illumination in an optical microscope?

Less diffraction results from the short wavelength of blue light

6. In a double slit experiment the slits are separated by 0.3096 mm and has a light with a wavelength of 589 nm. What is the angle of the 4<sup>th</sup> order minimum from the central maximum?

Convert: 0.3096 mm  $\rightarrow$  3.096 E -4 m and 589 nm  $\rightarrow$  589 E -9 m or 5.89 E -7 m

Remember the 4<sup>th</sup> dark fringe is between the 3<sup>rd</sup> and 4<sup>th</sup> bright fringe so  $m = 3$

$$d(\sin\theta) = (m + \frac{1}{2})\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow \theta = \sin^{-1}([(m + \frac{1}{2})\lambda]/d) \rightarrow \theta = \sin^{-1}([(3 + \frac{1}{2})(589 \text{ E } -9)]/(3.096 \text{ E } -4)) \rightarrow \underline{0.38^\circ}$$

## INTERFERENCE AND DIFFRACTION EVALUATION

**Name:** \_\_\_\_\_ **Date:** \_\_\_\_\_ **Period:** \_\_\_\_\_

**Please circle your answers for mathematical problems and you must show your work to earn any partial credit.**

**Constructive Interference:  $d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots$**

**Destructive Interference:  $d(\sin\theta) = (m + \frac{1}{2})\lambda$   $m = 0, \pm 1, \pm 2, \dots$**

**Diffraction:  $d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots$**

$$y = L \tan \theta$$

- 1) A neon-laser with a wavelength of 633 nm is pointed at a diffraction grating 3000 lines/cm. Find the angle where the first bright fringe occurs?
- 2) In a double slit interference experiment the second order maximum is observed at an angle of  $8.53^\circ$  from the central maximum. The wavelength of the light source is 500 nm. Calculate the slit's separation.
- 3) Your car has two headlights. What sort of interference pattern do you expect to be seen from them? Explain.

- 4) Light with a wavelength of 650 nm is shone on a grating. The angle between the zero and third order bright fringe is  $31.5^\circ$ . A) Calculate the spacing between the slits on the grating. B) Calculate the number of lines/m on the grating.
- 5) A diffraction grating having 400,000 lines/m has a 600 nm light source shone on it. Calculate the angle between the zero maximum and the first order maximum.
- 6) A prism separates colors of light by \_\_\_\_\_. A diffraction grating separates colors of light by \_\_\_\_\_.
- 7) The second order maximum fringe is obtained at an angle of  $19^\circ$ . The grating has 300 lines/mm. What is the wavelength of the light?
- 8) Describe the changes in a single-slit diffraction pattern as the width of the slit is decreased.

9) Two slits are 0.05 mm apart. A laser of wavelength 633 nm is incident to the slits. A) Calculate the angle of the third dark fringe.

10) Monochromatic light ( $\lambda = 441$  nm) is shone upon a narrow slit. On a screen 2 m away, the distance between the second diffraction minimum and the central maximum is 1.5 cm. What is the width of the slit?

## ANSWER KEY: INTERFERENCE AND DIFFRACTION EVALUATION

Name: \_\_\_\_\_ Date: \_\_\_\_\_ Period: \_\_\_\_\_

Please circle your answers for mathematical problems and you must show your work to earn any partial credit.

**Constructive Interference:**  $d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots$

**Destructive Interference:**  $d(\sin\theta) = (m + \frac{1}{2})\lambda$   $m = 0, \pm 1, \pm 2, \dots$

**Diffraction:**  $d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots$

$$y = L \tan\theta$$

- 1) A neon-laser with a wavelength of 633 nm is pointed at a diffraction grating 3000 lines/cm. Find the angle where the first bright fringe occurs?

Convert: 633 nm  $\rightarrow$  633 E - 9 m or 6.33 E - 7 m; 3000 lines/cm  $\rightarrow$  3.33 E -4 cm  $\rightarrow$  3.33 E -6 m

1<sup>st</sup> order:  $d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots \rightarrow \theta = \sin^{-1}(m\lambda/d) \rightarrow \theta = \sin^{-1}([(1)(633 \text{ E } -9)]/(3.33 \text{ E } -6))$

10.96°

- 2) In a double slit interference experiment the second order maximum is observed at an angle of 8.53° from the central maximum. The wavelength of the light source is 500 nm. Calculate the slit's separation.

Convert: 500 nm  $\rightarrow$  500 E -9 m or 5 E -7 m

$d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots \rightarrow d = m\lambda/\sin\theta \rightarrow d = [(2)(500 \text{ E } -9)]/\sin 8.53^\circ \rightarrow$

6.74 E - 6 m

- 3) Your car has two headlights. What sort of interference pattern do you expect to be seen from them? Explain.

None. Headlights are not coherent sources (cannot produce sustained interference patterns)

Bonus points: the headlights are so far apart in comparison to the wavelength emitted that even if they were made into coherent sources, the interference maximum and minimum would be too closely spaced to be observed.

- 4) Light with a wavelength of 650 nm is shone on a grating. The angle between the zero and third order bright fringe is 31.5°. A) Calculate the spacing between the slits on the grating. B) Calculate the number of lines/m on the grating.

Convert: 650 nm  $\rightarrow$  650 E -9 m or 6.5 E -7 m

A)  $d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots \rightarrow d = m\lambda/\sin\theta \rightarrow d = [(3)(650 \text{ E } -9)]/\sin 31.5^\circ \rightarrow$

3.73 E -6 m

B)  $(3.73 \text{ E } -6 \text{ m})^{-1} \rightarrow 267,947.98 \text{ lines/m} \rightarrow 2.7 \text{ E } +5 \text{ lines/m}$

- 5) A diffraction grating having 400,000 lines/m has a 600 nm light source shone on it. Calculate the angle between the zero maximum and the first order maximum.

Convert: 600 nm  $\rightarrow$  600 E -9 m or 6 E -7 m; 400,000 lines/m  $\rightarrow$  2.5 E -6 m

1<sup>st</sup> order:  $d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots \rightarrow \theta = \sin^{-1}(m\lambda/d) \rightarrow \theta = \sin^{-1}([(1)(600 \text{ E } -9)]/(2.5 \text{ E } -6))$

13.89°

- 6) A prism separates colors of light by refraction. A diffraction grating separates colors of light by interference.

- 7) The second order maximum fringe is obtained at an angle of 19°. The grating has 300 lines/mm. What is the wavelength of the light?

Convert: 300 lines/mm  $\rightarrow$  3.33 E -3 mm  $\rightarrow$  3.33 E -6 m

$d(\sin\theta) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots \rightarrow \lambda = d(\sin\theta)/m \rightarrow \lambda = (3.33 \text{ E } -6)(\sin 19^\circ)/2 \rightarrow$

5.42 E -7 m or 542 nm

- 8) Describe the changes in a single-slit diffraction pattern as the width of the slit is decreased.

The bands get wider and dimmer. Longer wavelengths will produce fringes with greater spacing on the screen because the spacing is directly proportional to the wavelength.

9) Two slits are 0.05 mm apart. A laser of wavelength 633 nm is incident to the slits. A) Calculate the angle of the third dark fringe.

Convert: 0.05 mm  $\rightarrow$  5 E -5 m; 633 nm  $\rightarrow$  633 E -9 m or 6.33 E -7 m

Remember the 3<sup>rd</sup> dark fringe is between the 2<sup>nd</sup> and 3<sup>rd</sup> bright fringe so  $m = 2$

$$d(\sin\theta) = (m + \frac{1}{2})\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow \theta = \sin^{-1}([(m + \frac{1}{2})\lambda]/d) \rightarrow \theta = \sin^{-1}([(2 + \frac{1}{2})(633 \text{ E } -9)]/(5 \text{ E } -5)) \rightarrow$$

$$\underline{1.81^\circ}$$

10) Monochromatic light ( $\lambda = 441 \text{ nm}$ ) is shone upon a narrow slit. On a screen 2 m away, the distance between the second diffraction minimum and the central maximum is 1.5 cm. What is the width of the slit?

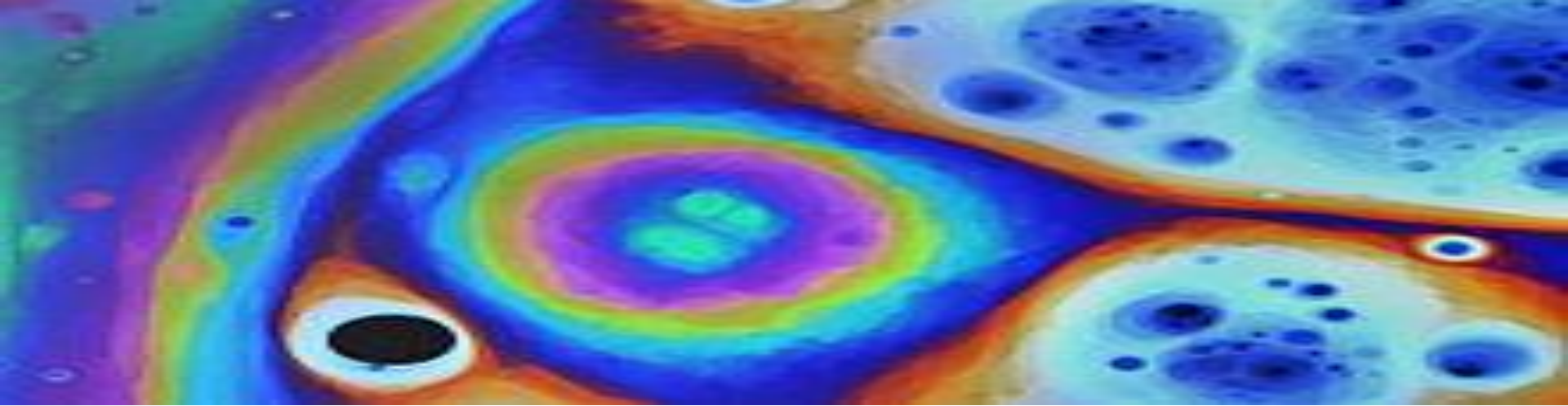
Convert:  $\lambda = 441 \text{ nm} \rightarrow 441 \text{ E } -9 \text{ m}$  or  $4.41 \text{ E } -7 \text{ m}$ ;  $1.5 \text{ cm} \rightarrow 0.015 \text{ m}$

$$L = 2 \text{ m} \quad y = 0.015 \text{ m} \quad m = (1 + \frac{1}{2}) \quad \theta = ? \quad d = ?$$

$$\text{First find angle: } y = L \tan\theta \rightarrow \theta = \tan^{-1}(y/L) \rightarrow \theta = \tan^{-1}[(0.015)/2] = \underline{0.43^\circ}$$

Remember the 2<sup>nd</sup> dark fringe is between the 1<sup>st</sup> and 2<sup>nd</sup> bright fringe so  $m = 1$

$$d(\sin\theta) = (m + \frac{1}{2})\lambda \quad m = 0, \pm 1, \pm 2, \dots \rightarrow d = (m + \frac{1}{2})\lambda/\sin\theta \rightarrow d = [(1 + \frac{1}{2})(441 \text{ E } -9)]/\sin 0.43^\circ \rightarrow$$
$$\underline{d = 8.81 \text{ E } -5 \text{ m}}$$



# LIGHT INTERFERENCE

# LIGHT WAVES COMBINE WITH EACH OTHER

- Interference takes place only between waves with the same wavelength.
- Monochromatic: light waves that have the same wavelength.
- Constructive: light becomes brighter
- Destructive: light becomes dimmer

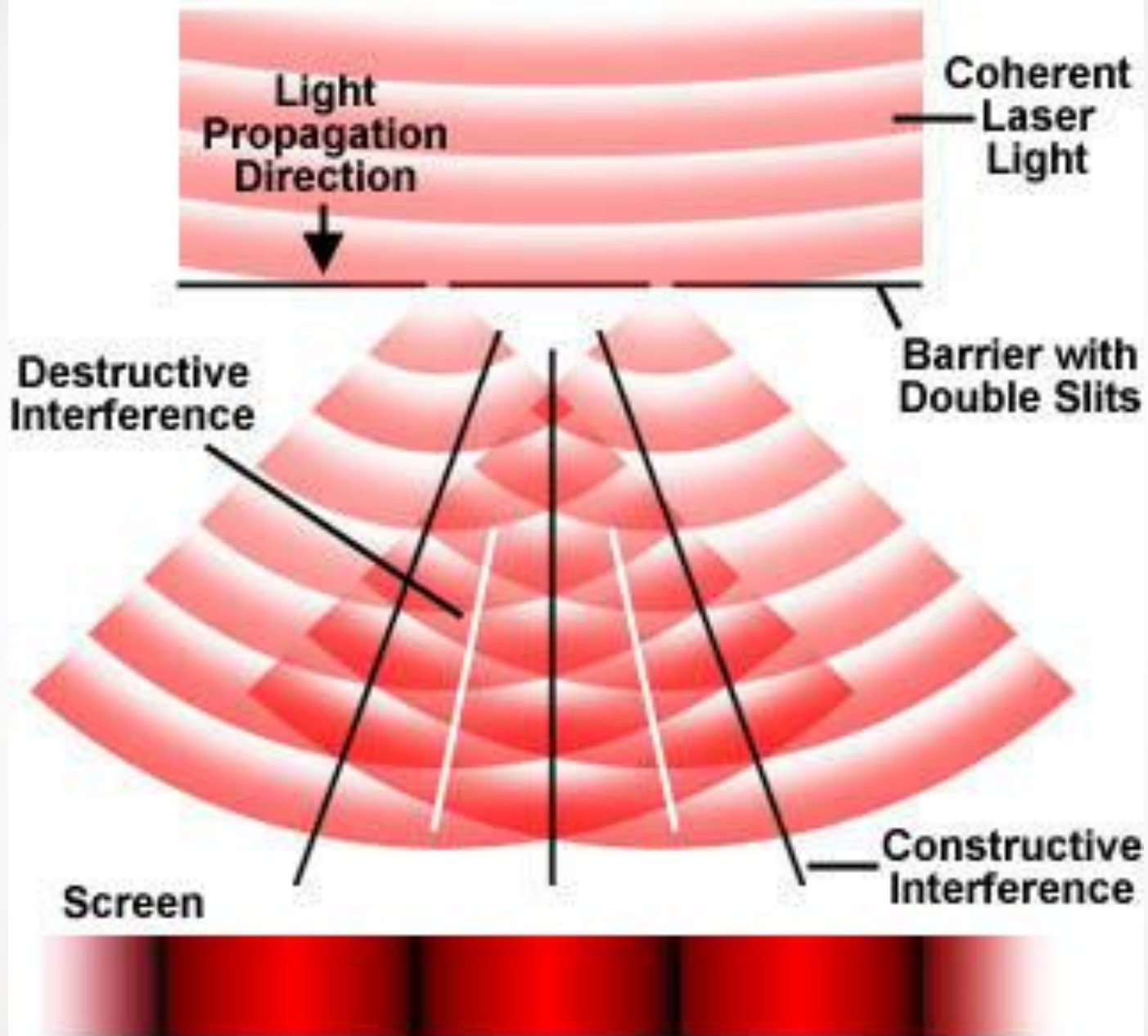
# INTERFERENCE

- Waves must have a constant phase difference for interference to be observed.
- Crest 1 + Crest 2 = phase difference of  $0^\circ$  and said to be in phase.
- Crest 1 + Trough 2 = phase difference of  $180^\circ$  and said to be out of phase.
- When the phase difference between two waves is constant and the waves do not shift relative to each other as time passes, the waves are said to have coherence.

# DEMONSTRATING INTERFERENCE

- Light from a single source is passed through a narrow slit and then through two narrow parallel slits. The slits serve as a pair of coherent light sources because the waves emerging from them come from the same source.
- If monochromatic light is used, the light from the two slits produces a series of bright and dark parallel bands (fringes).

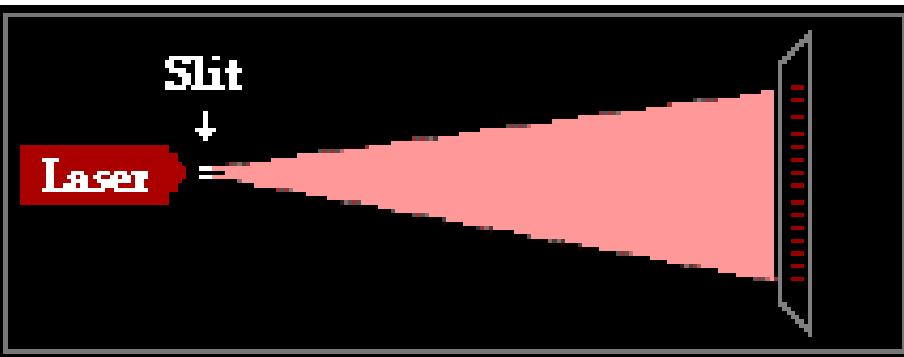
# Young's Double Slit Experiment



**Figure 4** Intensity Distribution of Fringes

## Results of Young's Experiment

Top View of Experimental Set-Up



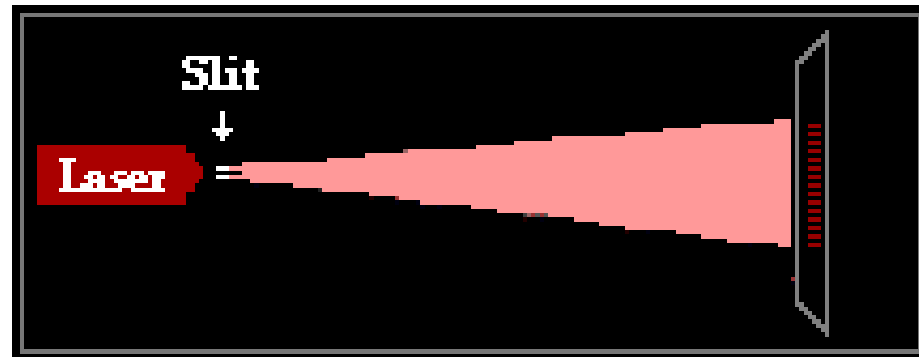
Front View of Screen



Low frequency

Large spacing between bright bands.

Top View of Experimental Set-Up

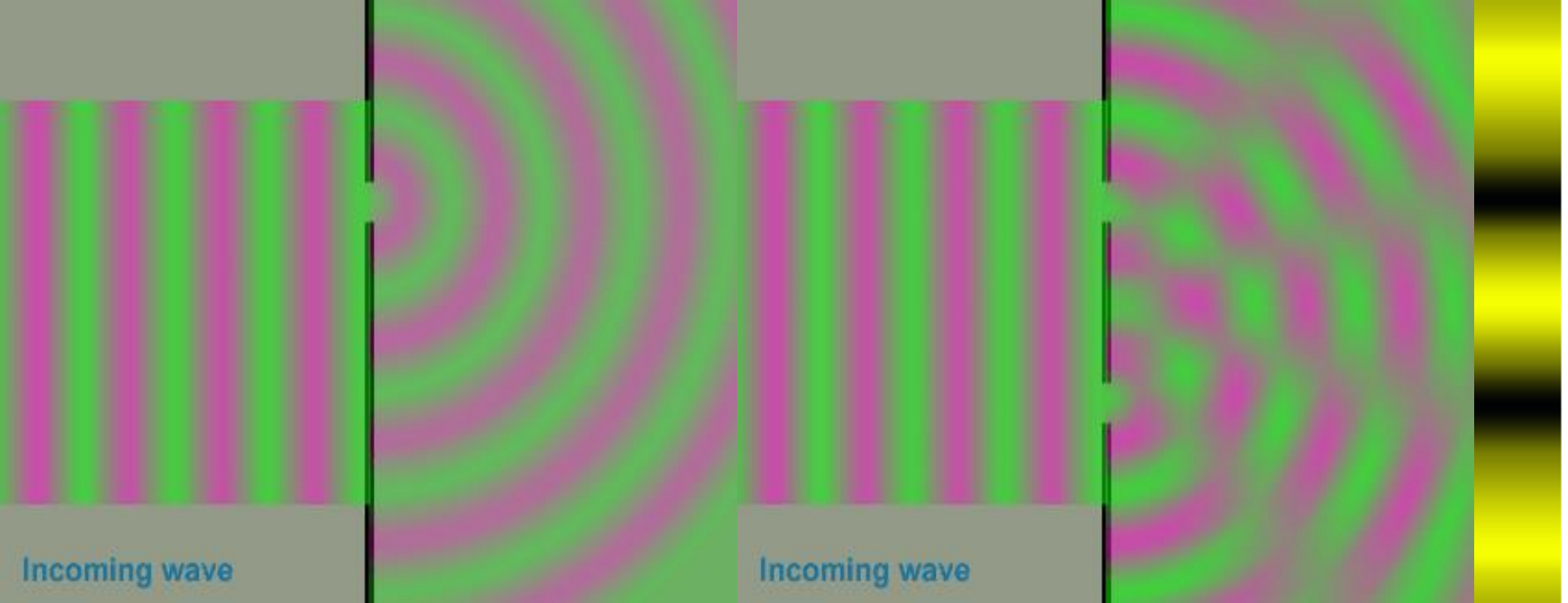


Front View of Screen

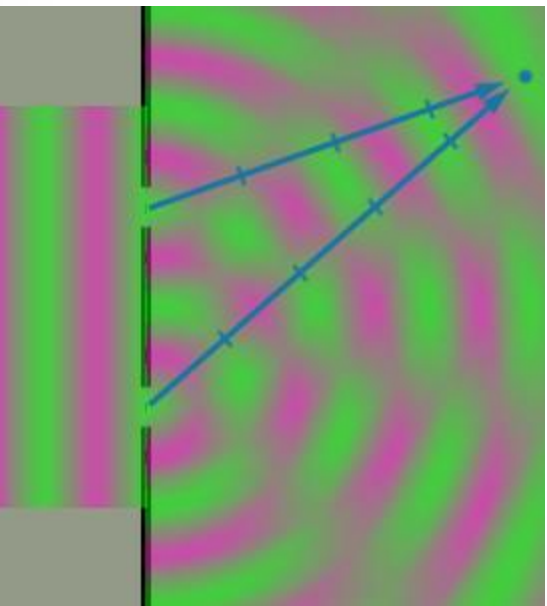


High frequency

Small spacing between bright bands.

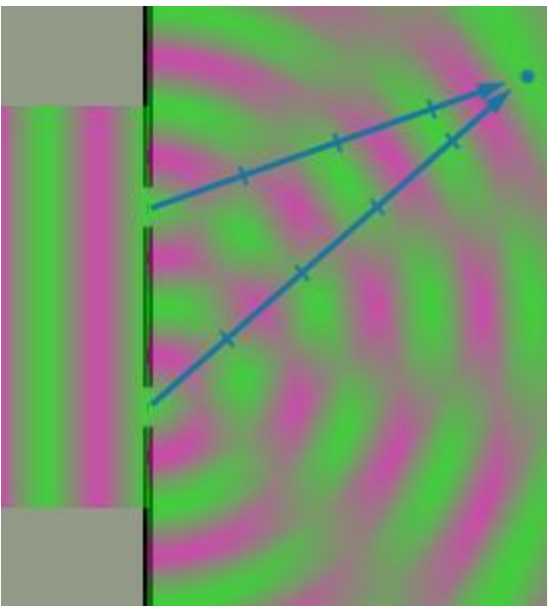


## Single Slit



- **Destructive Interference**

## Double Slit



- **Constructive Interference**

# PREDICTING THE LOCATION OF INTERFERENCE FRINGES

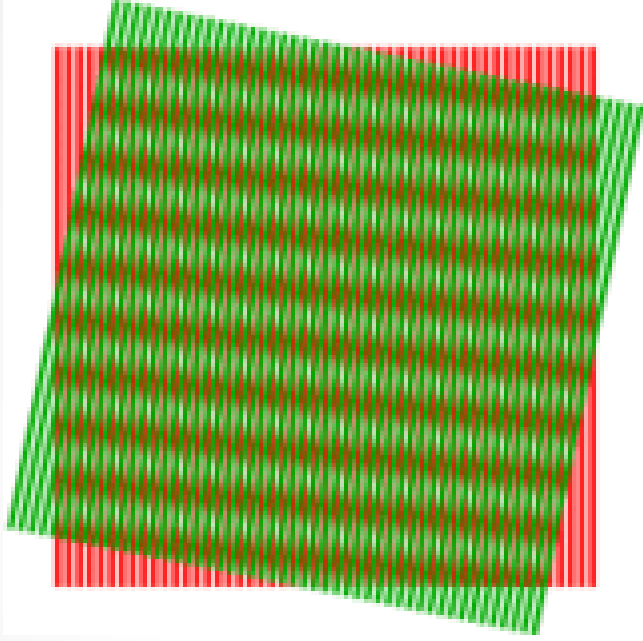
- Path difference: the difference in the distance traveled by two interfering light waves.
- Constructive:  $d (\sin\theta) = m\lambda$
- Destructive:  $d (\sin\theta) = (m + \frac{1}{2})\lambda$   
(odd #  $\lambda$ )
- Order number (m): the number assigned to interference fringes with respect to the central bright fringes)

# MOIRE' PATTERNS AND INTERFERENCE

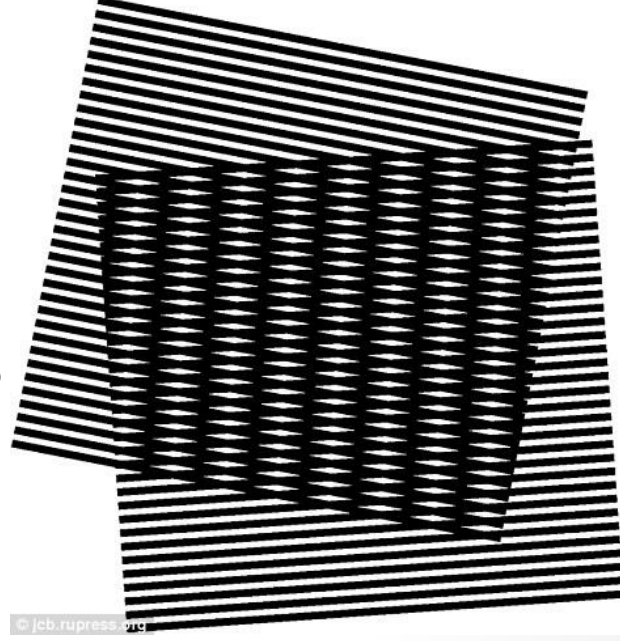
- Moiré patterns due to interference are created by two similar grids overlapping each other. A series of fringe patterns that change shape are produced when the grids are moved.
- Moiré patterns are often an unwanted product of images created by many computer and digital imaging/graphics techniques.

# MOIRE' PATTERNS

[http://en.wikipedia.org/wiki/Moir%C3%A9\\_pattern](http://en.wikipedia.org/wiki/Moir%C3%A9_pattern)



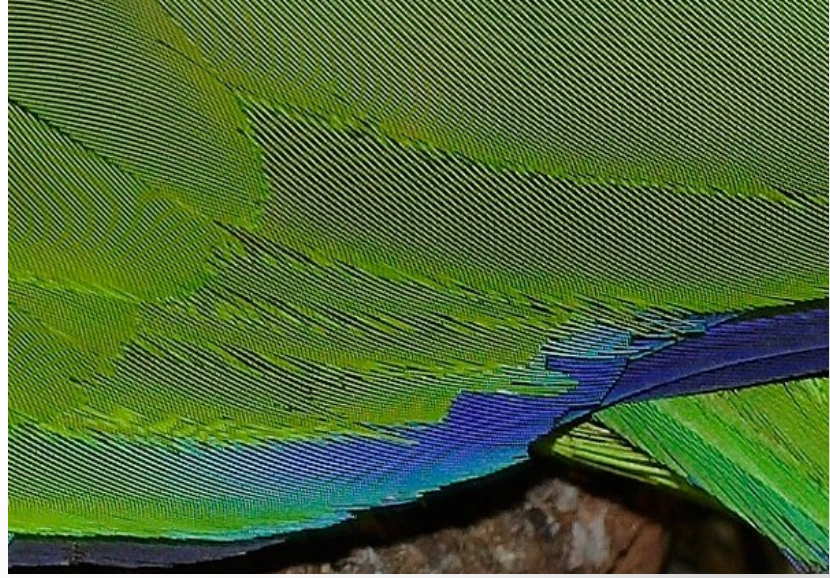
<http://www.dailymail.co.uk/news/article-2096924/Rug-makes-seasick.html>



<http://photographylife.com/what-is-moire;> (Image courtesy of [photo.net](http://photo.net))

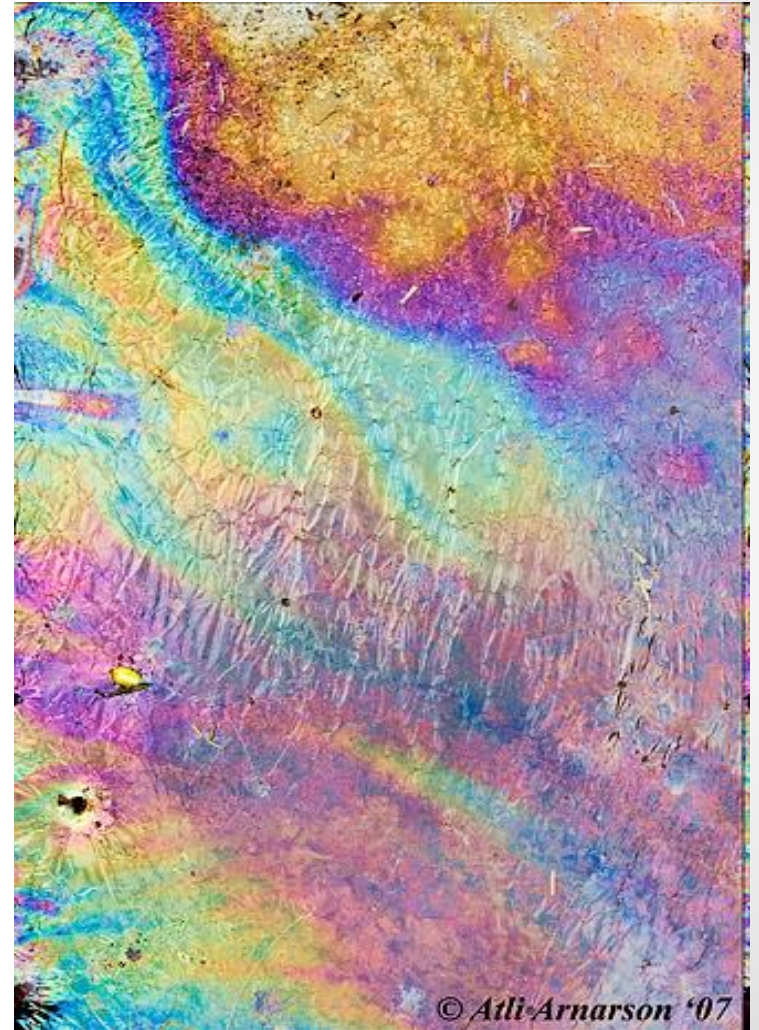


[http://en.wikipedia.org/wiki/Moir%C3%A9\\_pattern#mediaviewer/File:Moir%C3%A9\\_parrot\\_feathers.jpg](http://en.wikipedia.org/wiki/Moir%C3%A9_pattern#mediaviewer/File:Moir%C3%A9_parrot_feathers.jpg)



# IRIDESCENCE

- Objects that show a rainbow of colors which can change depending on our point of view, are considered iridescent.
- Iridescence is from the Latin word, "iris," meaning rainbow.
- Iridescence is caused by "structural colors" rather than pigment molecules.



# Examples of Interference in Nature



Peacock Feather



Abalone Shell



Iridescent Opal

Figure 9

<http://www.microscopyu.com/articles/polarized/interferenceintro.html>



<http://nine-radical.blogspot.com/2007/04/8-eye-evolution-wars-of-perfection.html>



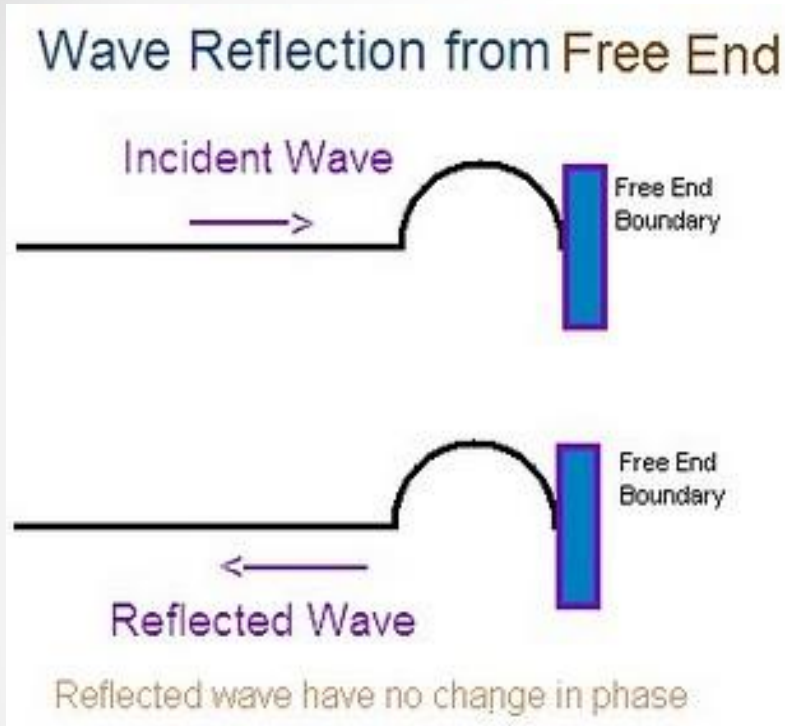
<http://www.itp.uni-hannover.de/~zawischa/ITP/multibeam.html>

# CAUSE OF IRIDESCENCE

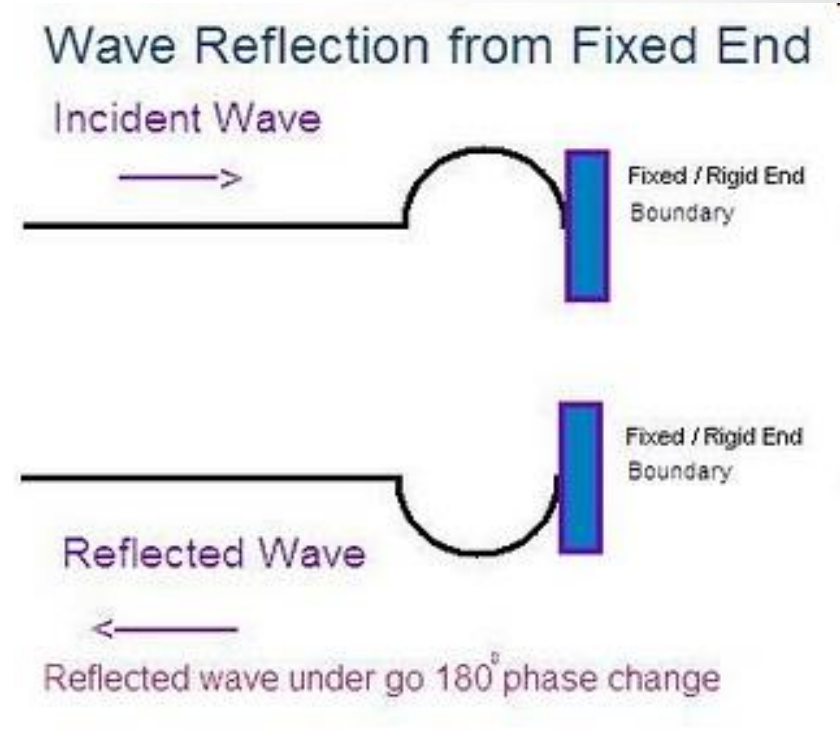
- Constructive and destructive interference of different wavelengths of light produces different colors when viewed at different angles of incident light.
- Seen with thin-films (Soap Bubbles, Oil on Water) or with diffraction gratings (pearls, CDs).
- Colors seen are due to:
  - index of refraction
  - thickness of the film/grating
  - wavelength of light
  - angle of incidence

# REMEMBER: PHASE CHANGES AT BOUNDARIES

<http://snvphysics.blogspot.com/2011/03/waves.html>



A Free End boundary is similar to light entering a material with an index of refraction lower than the incident material. No phase shift occurs.



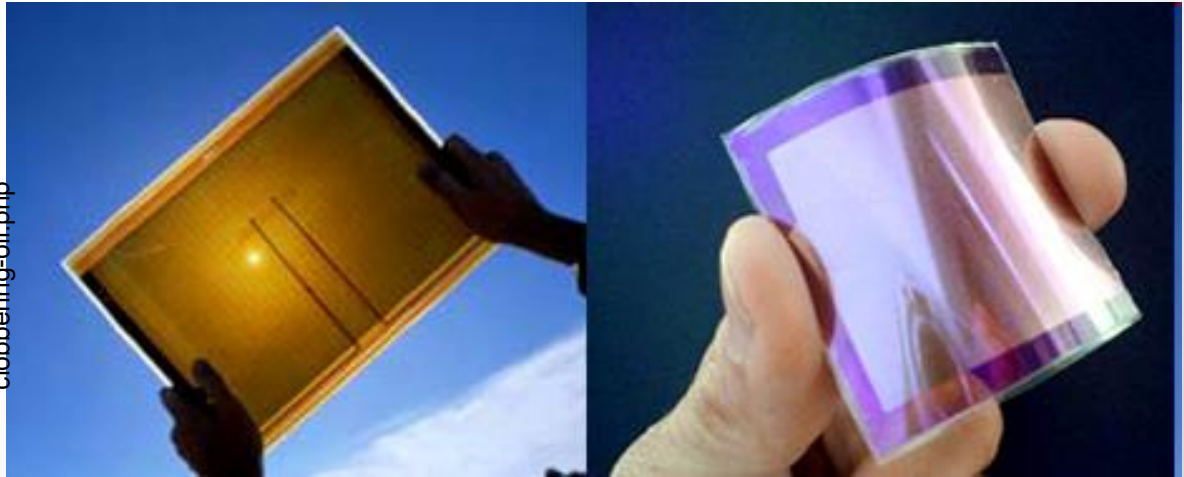
A Fixed End boundary is similar to light entering a material with an index of refraction higher than the incident material. An  $180^\circ$  phase shift occurs.

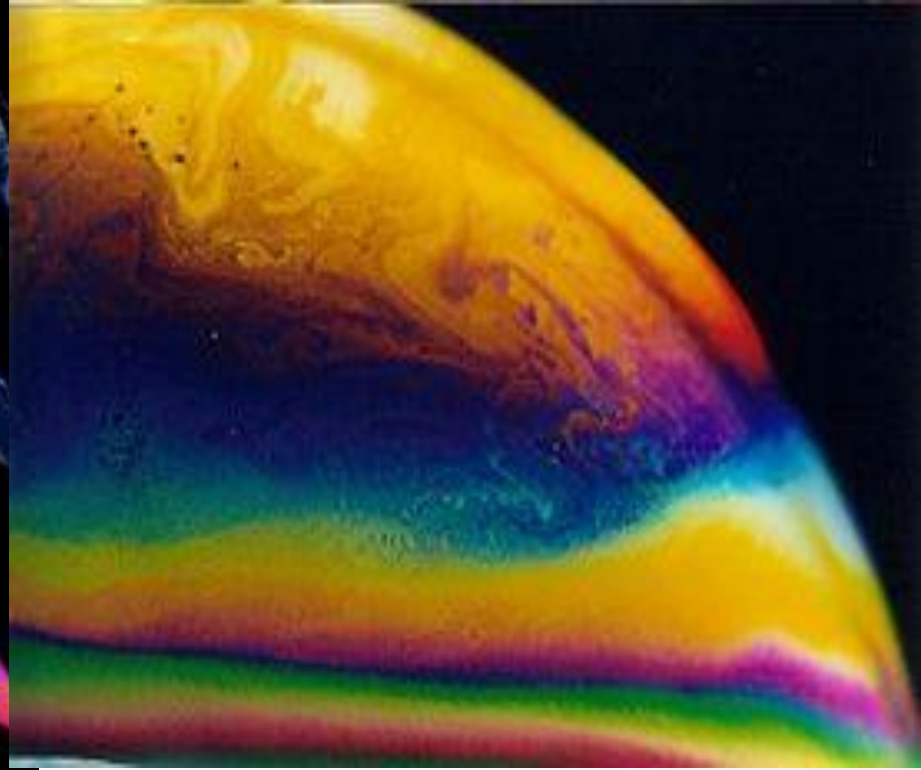
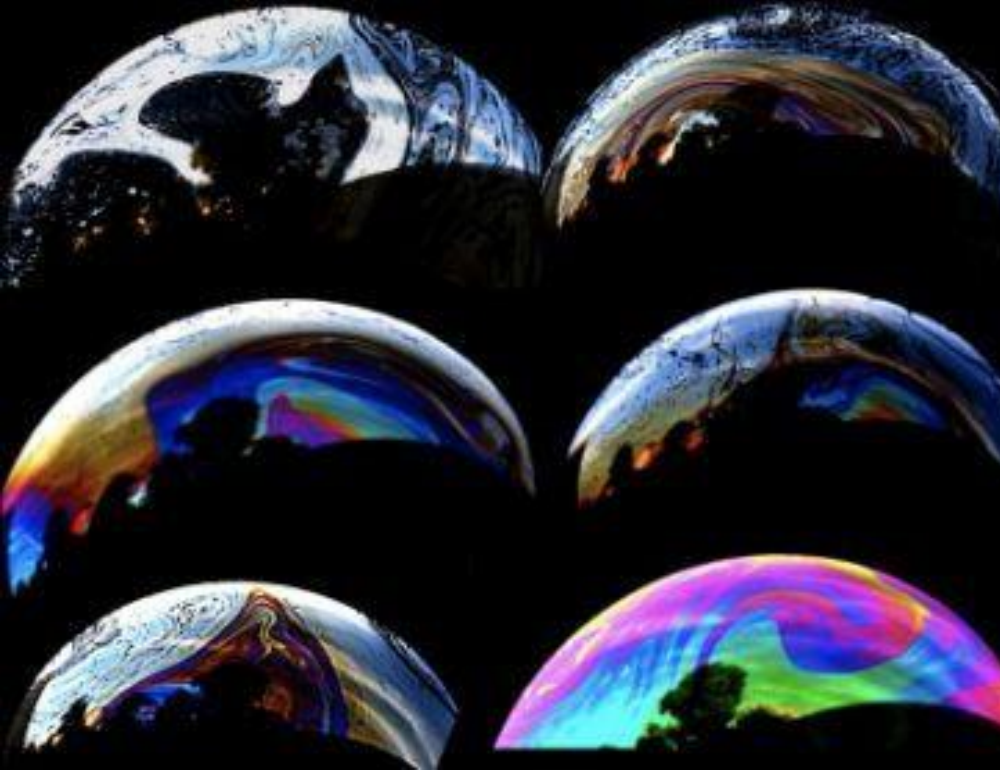
Only reflected waves can have phase shifts – Refracted waves do not.

# THIN-FILMS

- A thin film is a layer of material ranging from fractions of a nanometer to several micrometers in thickness. Electronic semi-conductor devices and optical coatings are the main applications benefitting from thin film construction.

<http://www.treehugger.com/files/2007/02/thinfilm-solar-clobbering-oil.php>





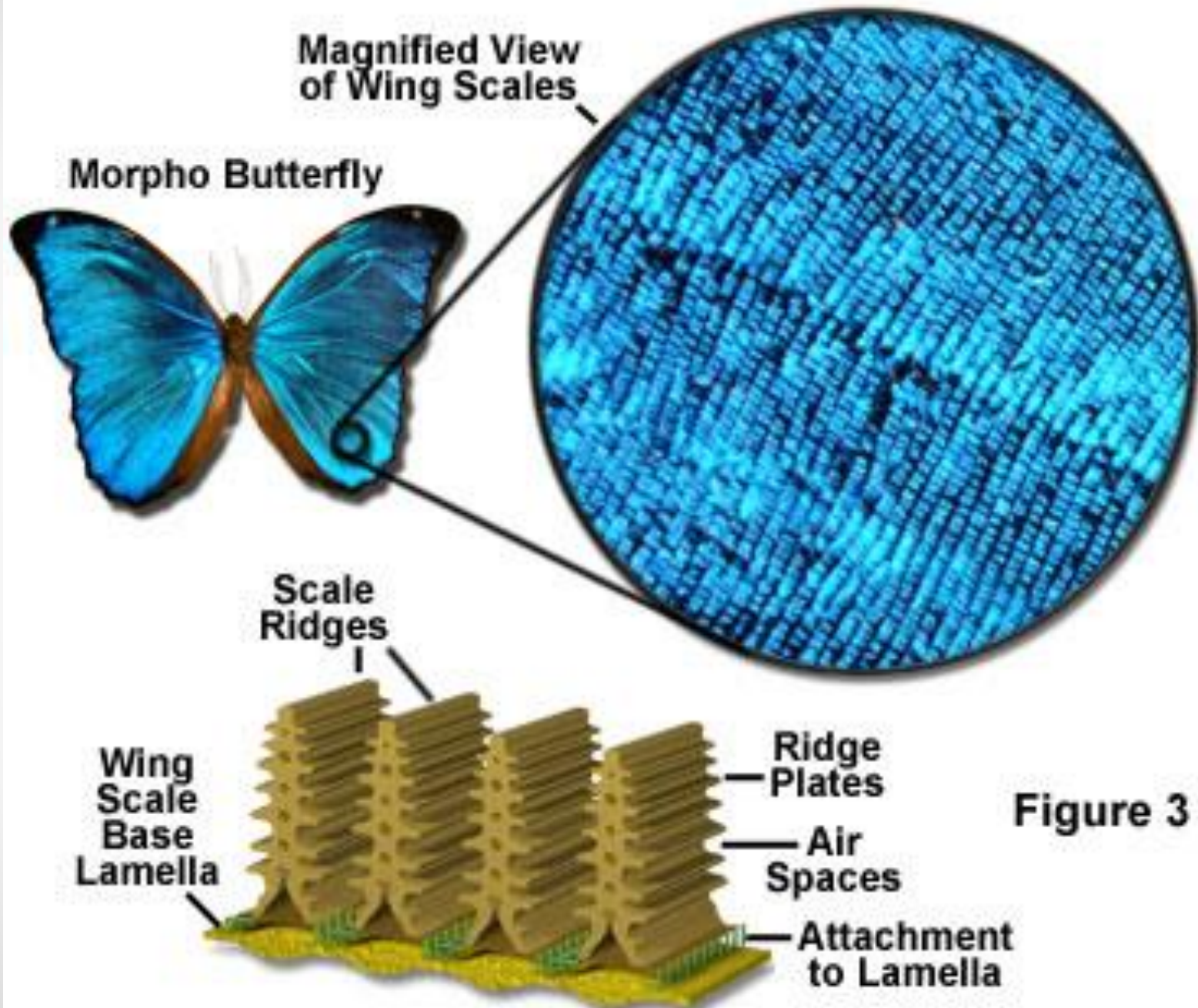
<http://www.statemaster.com/encyclopedia/Soap-bubble>



**As the film gets thin at the top it becomes black because its thickness is less than the wavelength of the visible light.**

[http://www.funsci.com/fun3\\_en/exper2/exper2.htm](http://www.funsci.com/fun3_en/exper2/exper2.htm)

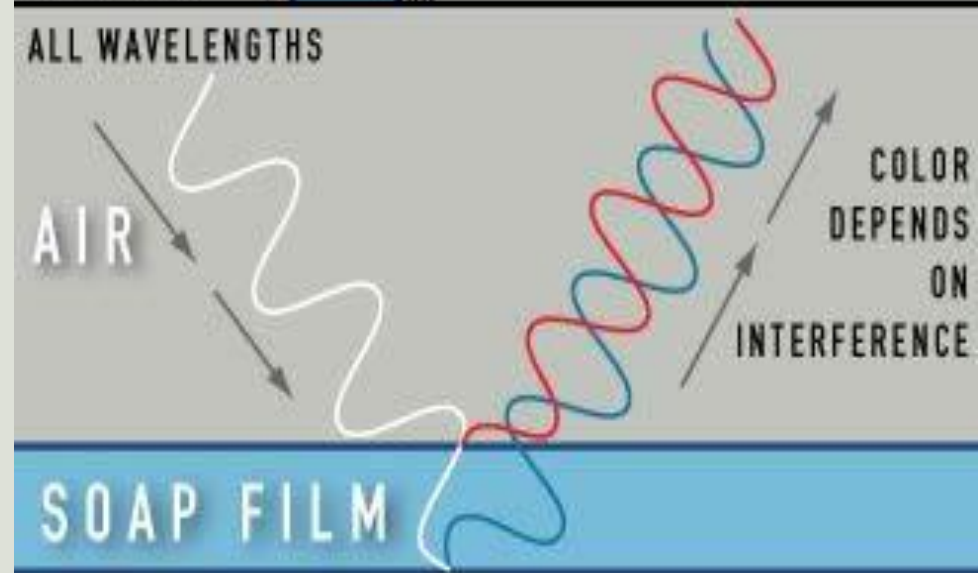
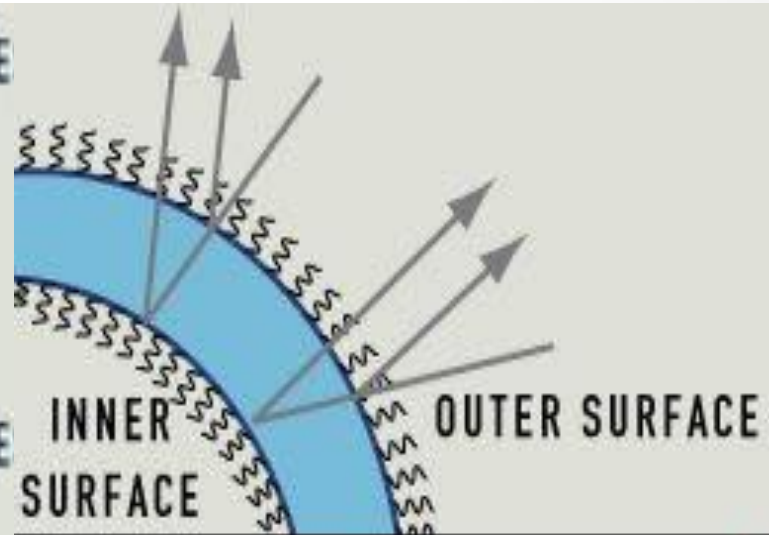
# Interference Structures in Butterfly Wings



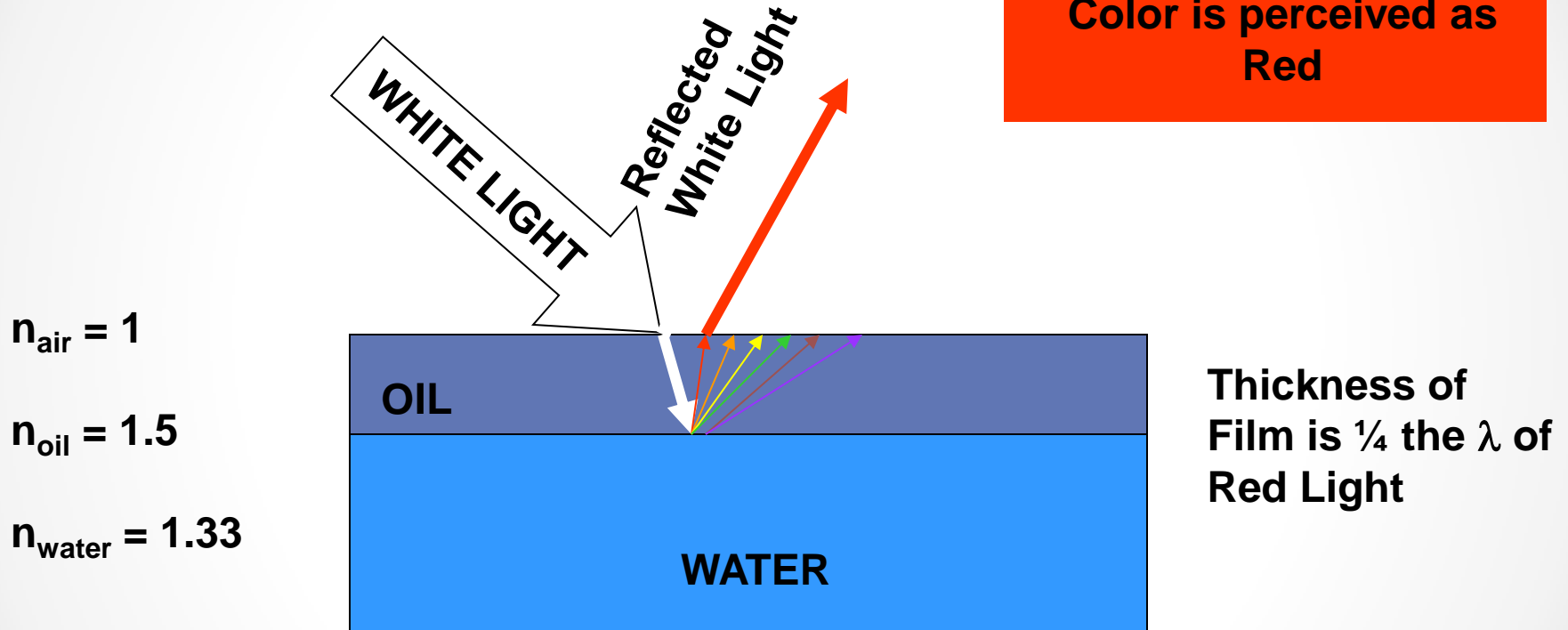
# CONSTRUCTIVE INTERFERENCE AND THIN-FILMS

- Ex) soap bubble or oil on water
- Light reflecting from the top has phase shift
- Light reflecting from the bottom has no phase change.
- Destructive interference would occur for most colors.
- But, if the thickness of the film is  $\frac{1}{4} \lambda$  (of a certain color of light) the light would travel an extra distance of  $\frac{1}{2} \lambda$ .
- This color's  $\lambda$  is in phase with the top reflected wave → film appears this color (Constructive Interference).

# INSIDE A SOAP BUBBLE



# THICKNESS OF FILM DETERMINES COLOR

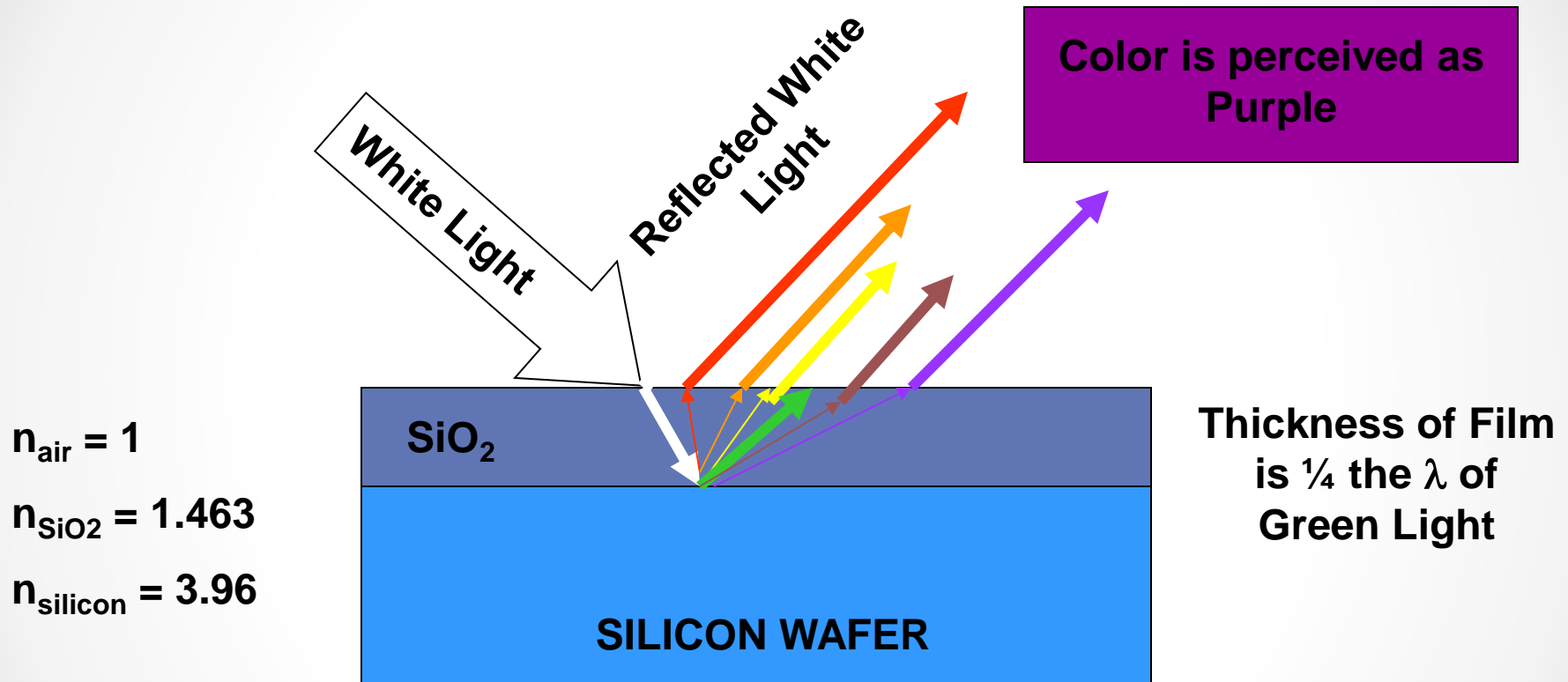


Red light reflected from the top surface interferes constructively with red light from the bottom surface, so the film looks red. Light of the other colors experiences destructive interference.

# DESTRUCTIVE INTERFERENCE AND THIN-FILMS

- Ex) non-reflective coatings and colors are seen on silicon wafers with a  $\text{SiO}_2$  thin-film.
- Since  $n_{\text{substrate}} > n_{\text{film}} > n_{\text{air}}$  both the top and bottom reflected waves have  $180^\circ$  phase shift.
- Most colors of light will constructively interfere.
- But, if the thickness of the film is  $\frac{1}{4} \lambda$  (of a certain color of light) the light would travel an extra distance of  $\frac{1}{2} \lambda$ .
- This color's  $\lambda$  is out of phase with the top reflected wave and cancels (Deconstructive Interference).
- The color seen is a mix of the other frequencies.

# THICKNESS OF FILM DETERMINES COLOR



Light reflecting from the bottom surface travels an extra distance of  $\frac{1}{2}$  the  $\lambda$  of green light. Green light reflected from the top surface interferes destructively with green light from the bottom surface. Most of the light in the middle region of the visible spectrum is transmitted and not reflected. Since some violet and red light is reflected the coating is perceived as purple.

# SPECTRUM APPLET

[http://www.cs.rit.edu/~ncs/color/a\\_spectr.html](http://www.cs.rit.edu/~ncs/color/a_spectr.html)

<b>Film Thickness (Å)</b>	<b>Color of Film</b>
-------------------------------	----------------------

500	tan
700	brown
1000	dark violet to red violet
1200	royal blue
1500	light blue to metallic blue
1700	metallic to very light yellow-green
2000	light gold or yellow - slightly metallic
2200	gold with slight yellow-orange
2500	orange to melon
2700	red-violet
3000	blue to violet-blue
3100	blue
3200	blue to blue-green
3400	light green
3500	green to yellow-green

The appearance of color is due to the constructive and destructive interference of light. The wavelengths of light in SiO<sub>2</sub> which undergo destructive interference is given by:

$$\lambda_k = (5.84t) / (2k + 1)$$

Where:

$\lambda$  = wavelength

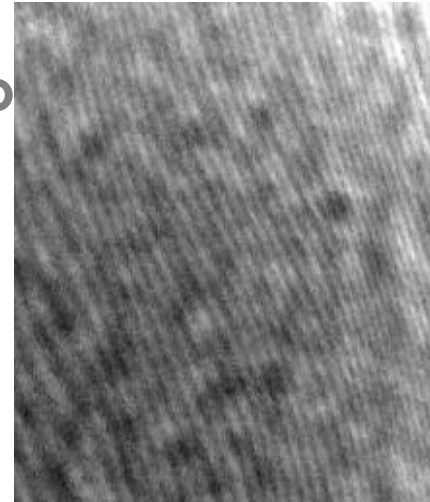
t = oxide thickness

k = 0, 1, 2, ... (and which give solutions in the visible light spectrum)

The color of light seen is the eyes response to the amplitude of the wavelengths remaining.

# HOLOGRAMS

- Holography depends on the coherent nature of laser light to create an interference pattern that produces a 3-D image when illuminated by a light source. Four main types: transmission, reflection, pulsed and embossed
- Many pairs of beams form an extremely complicated interference pattern on film, one that can be produced only if the phase relationship of the 2-wave pairs is constant throughout the exposure of the film. This condition is met through the use of light from a laser because of the coherence of laser light.



Close-up photograph of a hologram's surface (a toy van). Can not tell what it is similar to trying to identify what music has been recorded by looking at the surface of a CD. The hologram is defined by the speckle pattern, rather than the "wavy" line pattern.

<http://en.wikipedia.org/wiki/Holography>

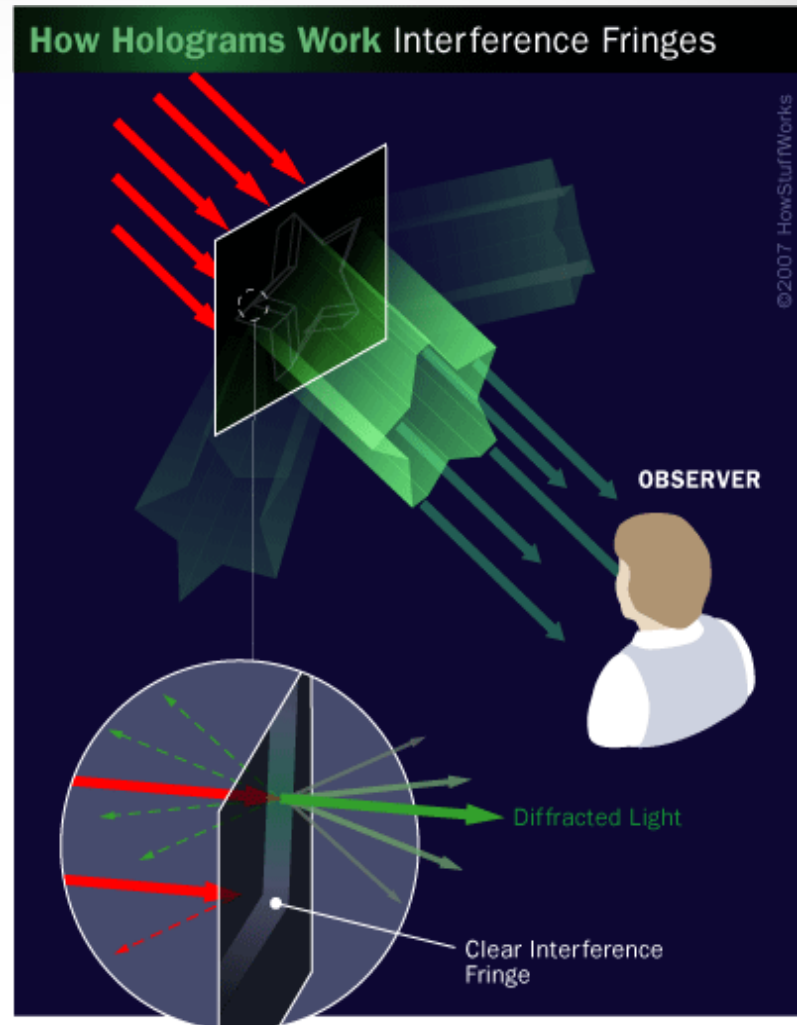
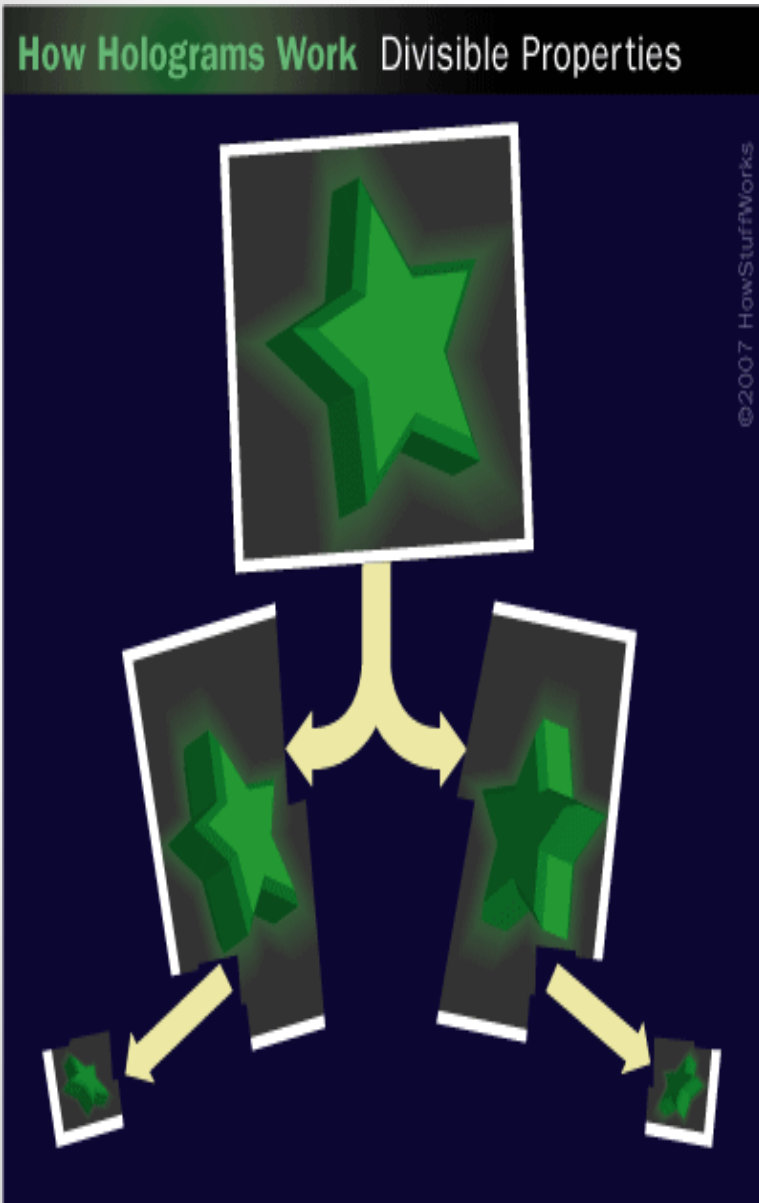
The holograms found on credit cards and other ordinary objects are embossed holograms mass-produced by stamping the pattern onto foil.



# SOME TYPES OF HOLOGRAMS

- **Transmission:** they should be lit from behind (like a slide in a slide projector). It can be difficult to light the hologram in this manner so a mirror or a foil backs the hologram.
- **Embossed:** are a type of transmission hologram; most common; can be massed produced quickly and cheaply; The original hologram is made into a metal copy and duplicates are used to create millions of copies by embossing the pattern into soft aluminized plastic.
- **Reflection:** the object and reference beams are incident on the plate from opposite sides of the plate. The reconstructed object is then viewed from the same side of the plate as that at which the re-constructing beam is incident.
- **Pulsed:** instead of a steady laser being directed on the image a rapidly pulsed laser is used. This reduces the need for vibrational tables.

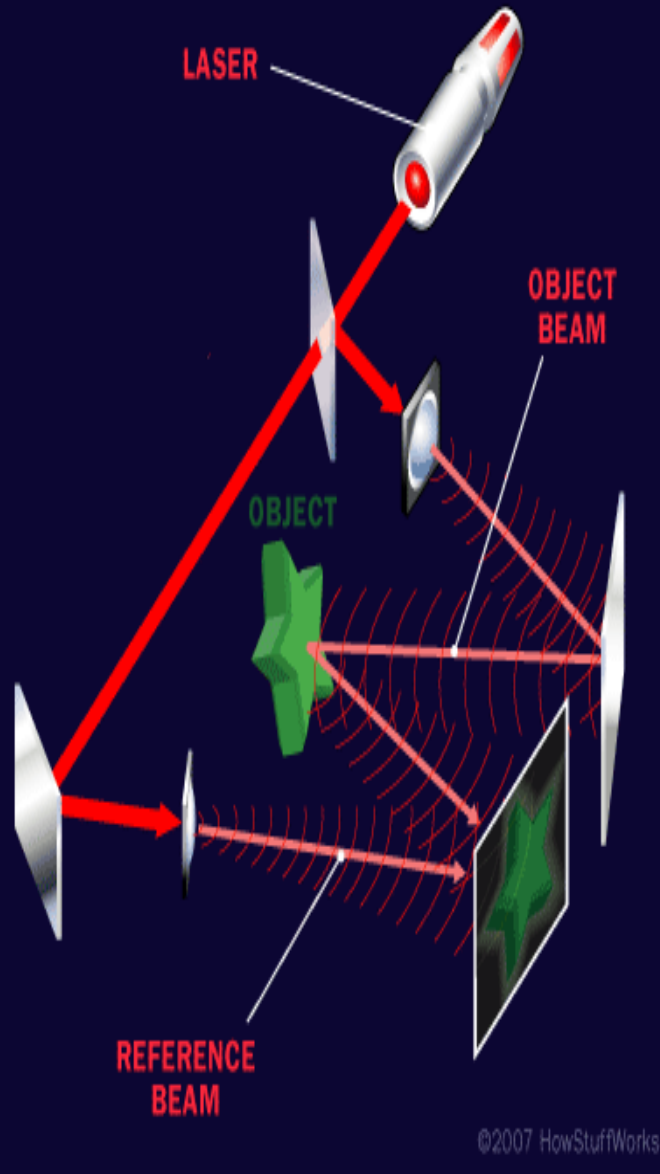
**If you tear a hologram in half, you can still see the whole image in each piece. The same is true with smaller and smaller pieces.**



**The interference fringes in a hologram cause light to scatter in all directions, creating an image in the process. The fringes diffract and reflect some of the light (inset), and some of the light passes through unchanged.**

# Basic transmission hologram:

- 1) The laser points at the beam splitter, which divides the beam of light into two parts.
- 2) Mirrors direct the paths of these two beams so that they hit their intended targets.
- 3) Two beams pass through a diverging lens and become a wide band of light rather than a narrow beam.
- 4) Object beam, reflects off of the object and onto the photographic emulsion.
- 5) The reference beam, hits the emulsion without reflecting off of anything other than a mirror.

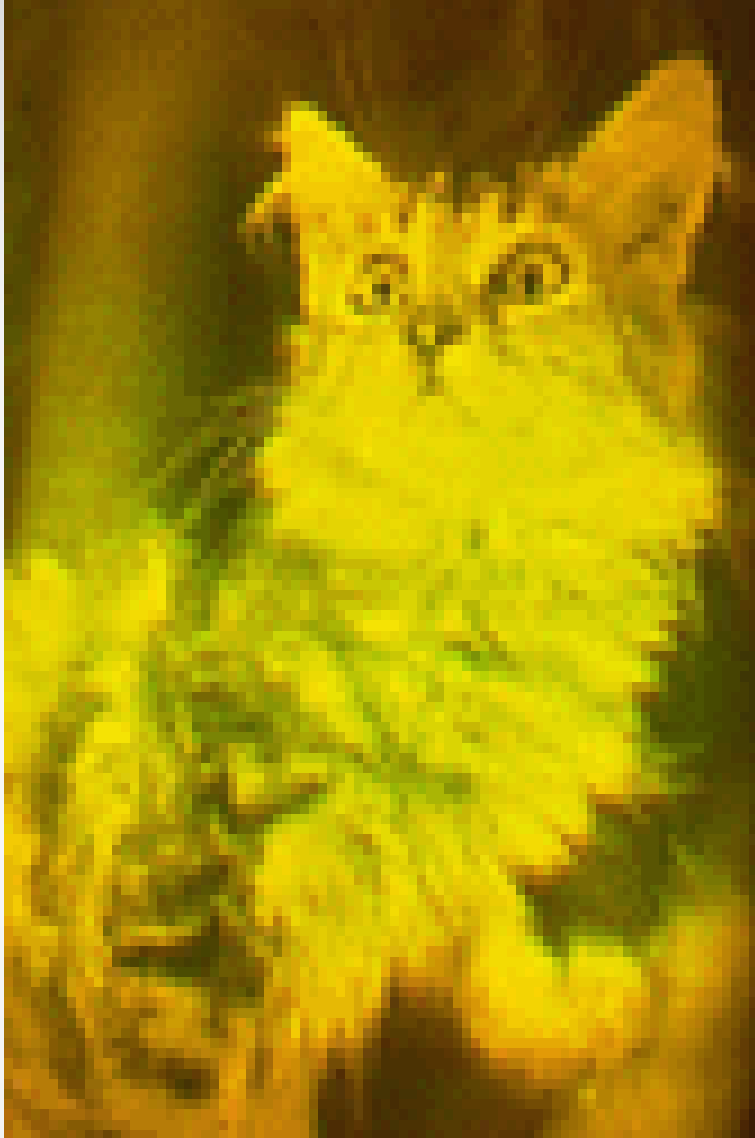


©2007 HowStuffWorks

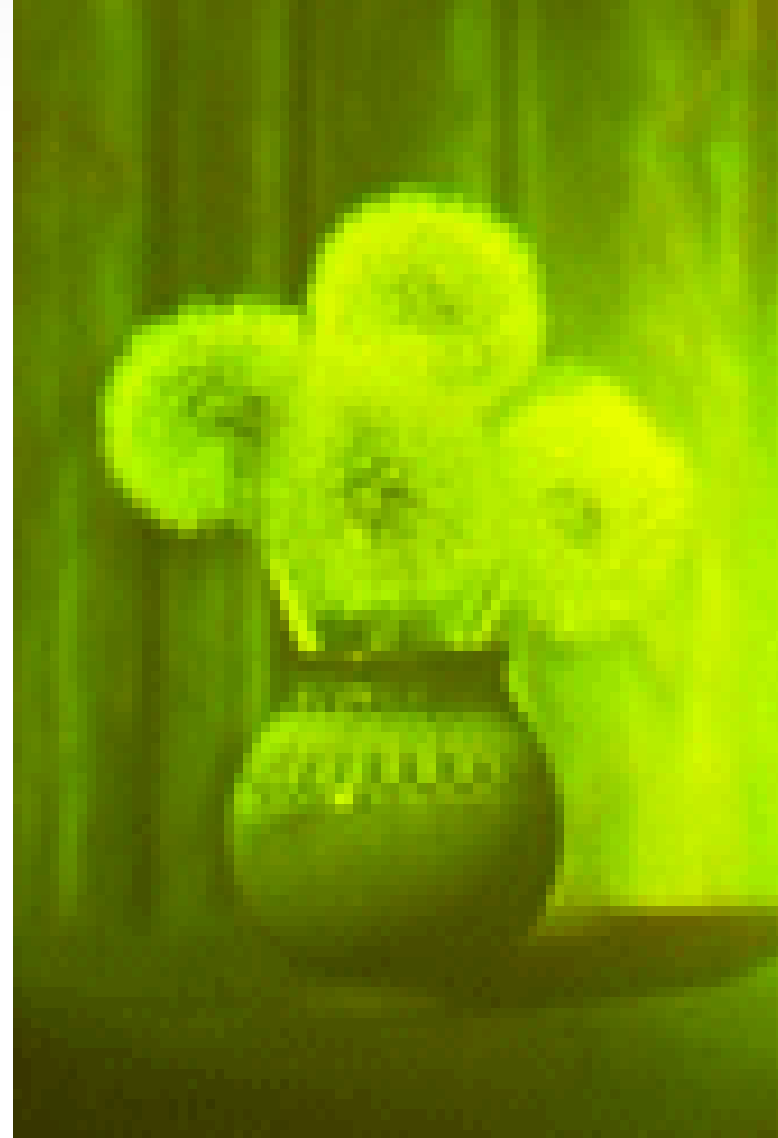


Example of a transmission hologram; usually can only be reconstructed using a laser but a particular type of transmission hologram, known as a rainbow hologram, can be viewed with white light.

<http://holographica.blogspot.com/2009/10/phila-delphia-holography-norristown.html>



**1- Channel:** You can see several views of kitten and "movement" of background. Although hologram was recorded on flat media, you can see full 3D illusion of the object.



**Multi-Channel:** "Channels" mean different images, recorded on the same hologram. Such images appear in a hologram one after another during observation. There are two channels within this picture.

# NSS: PHYSICAL SCIENCE

- **MOTIONS AND FORCES**

- Gravitation is a universal force that each mass exerts on any other mass. The strength of the gravitational attractive force between two masses is proportional to the masses and inversely proportional to the square of the distance between them.

- **CONSERVATION OF ENERGY AND THE INCREASE IN DISORDER**

- All energy can be considered to be either kinetic energy, which is the energy of motion; potential energy, which depends on relative position; or energy contained by a field, such as electromagnetic waves.

- **INTERACTIONS OF ENERGY AND MATTER**

- Waves, including sound and seismic waves, waves on water, and light waves, have energy and can transfer energy when they interact with matter
- Electromagnetic waves result when a charged object is accelerated or decelerated. Electromagnetic waves include radio waves (the longest wavelength), microwaves, infrared radiation (radiant heat), visible light, ultraviolet radiation, x-rays, and gamma rays. The energy of electromagnetic waves is carried in packets whose magnitude is inversely proportional to the wavelength.
- Each kind of atom or molecule can gain or lose energy only in particular discrete amounts and thus can absorb and emit light only at wavelengths corresponding to these amounts. These wavelengths can be used to identify the substance.

# GPS: PHYSICS

## **SP4. Students will analyze the properties and applications of waves.**

- a. Explain the processes that results in the production and energy transfer of electromagnetic waves.
- b. Experimentally determine the behavior of waves in various media in terms of reflection, refraction, and diffraction of waves.
- c. Explain the relationship between the phenomena of interference and the principle of superposition.
- e. Determine the location and nature of images formed by the reflection or refraction of light.

## **SP3. Students will evaluate the forms and transformations of energy.**

- a. Analyze, evaluate, and apply the principle of conservation of energy and measure the components of work-energy theorem by
  - • describing total energy in a closed system.
  - • identifying different types of potential energy.
  - • calculating kinetic energy given mass and velocity.
  - • relating transformations between potential and kinetic energy.
- b. Explain the relationship between matter and energy.
- e. Demonstrate the factors required to produce a change in momentum.

# REFERENCES

## Books:

Serway, Raymond A., and Jerry S. Faughn. Holt Physics. Austin, Texas: Holt, Rinehart and Winston, 2000.

White, Mary Anne. Properties of Materials. New York, New York: Oxford University Press, 1999.

## Websites:

“Agilent 101: An Introduction to Optical Spectroscopy” by Andrew Hind © Agilent 2000-2013, April 2011. Web. 11 June 2013.

[http://www.agilent.com/labs/features/2011\\_101\\_spectroscopy.html](http://www.agilent.com/labs/features/2011_101_spectroscopy.html)

“Anti-Reflective Coating” Wikipedia Wikimedia Foundation, Inc. 1 June 2011 Web. 15 June 2011. <[http://en.wikipedia.org/wiki/Anti-reflective\\_coating](http://en.wikipedia.org/wiki/Anti-reflective_coating)>

“Eyeglass Lens Coatings: Anti-Reflective, Scratch-Resistant, Anti-Fog and UV” by DeFranco, Liz and Heiting, Gary *All About Vision* © 2000-2011 Access Media Group LLC. December 2010 Web. 28 June 2011.

<http://www.allaboutvision.com/lenses/coatings.htm#ixzz1QbNR7uFp>

Georgia Tech Nanotechnology Research Center: *Equipment* ©2011 Georgia Institute of Technology n.d. Web. 20 June 2011.

<http://grover.mirc.gatech.edu/equipment/textInstructions.php?id=88>

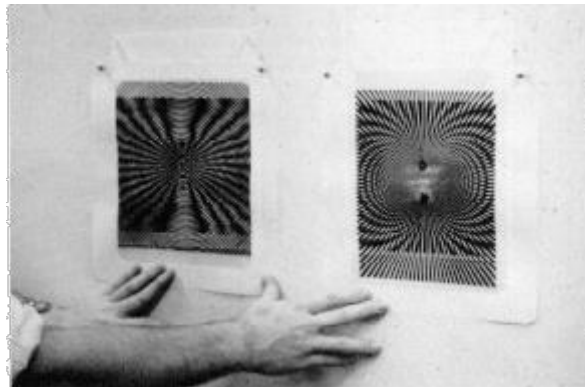
“How do Holograms Work” by Tracy V. Wilson *How Stuff Works: A Discovery Company*. © 1998-2011 HowStuffWorks, Inc. n.d. Web. 14 July 2011. <http://science.howstuffworks.com/hologram.htm>

# REFERENCES

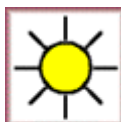
- “How do Photovoltaics Work” by Gil Knier NASA SCIENCE: Science News  
NASA 6 April 2011 Web. 5 July  
2011. <http://science.nasa.gov/science-news/science-at-nasa/2002/solarcells/>
- “Introduction to Physics. Final Study Guide > Light” engrade. n.d. Web. 12  
June 2013. <https://wikis.engage.com/physicsintro/physicsintro27>
- “Iridescent Colors Caused by Interference: Iridescence”. Causes of  
Color n.d. Web. 29 June 2011.  
<http://www.webexhibits.org/causesofcolor/15.html>
- “Moire’ Pattern” Wikipedia Wikimedia Foundation, Inc. 26 May 2014  
Web. 06 June 2014.<  
[http://en.wikipedia.org/wiki/Moir%C3%A9\\_pattern](http://en.wikipedia.org/wiki/Moir%C3%A9_pattern)>
- “Optical Coating” Wikipedia Wikimedia Foundation, Inc. 13 June 2010  
Web. 15 June 2011.< [http://en.wikipedia.org/wiki/Optical\\_coating](http://en.wikipedia.org/wiki/Optical_coating) >
- “Pioneers in Optics: Friedrich Johann Karl Becke”. Molecular Expressions:  
Science, Optics and You © 1998-2010 Michael E. Davidson and the  
Florida State University. 18 November 2006 Web. 29 June 2011.  
<http://micro.magnet.fsu.edu/optics/timeline/people/becke.html>
- “Theory and Fabrication of Integrated Circuits: GT7 – SiO<sub>2</sub> Color Chart”  
ECE Illinois Copyright © 2007, 2008, 2009, 2010, 2011 The Board of  
Trustees at the University of Illinois. n.d. Web. 28 June 2011.  
<http://fabweb.ece.uiuc.edu/gt/gt/gt7.aspx>
- “Thin-Film Battery Attains Commercial Availability” ThinFilmsBlog 13  
December 2007 Web. 28 June 2011.  
<<http://www.thinfilmsblog.com/2007/12/thin-film-battery-attains-commercial.html>>

# REFERENCES

- “Thin Film Battery Overview” Copyright © 2011 Oak Ridge Micro-Energy, 3 January 2011 Web. 15 June 2011  
<<http://www.oakridgemicro.com/tech/tfb.htm#up>>



Perception



Light

## Moiré Patterns

When you overlap materials with repetitive lines, you create moiré patterns.

When you look through one chain-link fence at another, you sometimes see a pattern of light and dark lines that shifts as you move. This pattern, called a *moiré pattern*, appears when two repetitive patterns overlap. Moiré patterns are created whenever one semitransparent object with a repetitive pattern is placed over another. A slight motion of one of the objects creates large-scale changes in the moiré pattern. These patterns can be used to demonstrate wave interference.

### materials

- **2 identical pocket combs**, or a pocket comb and a mirror.
- **2 pieces of window screen**, or a window screen, a sheet of white cardboard, and a bright light.
- **Access to a copy machine.**
- **2 transparencies** made from the pattern provided in this Snack. (See Etc. for other suggestions.)
- **third materials item**
- **Optional:** Moiré patterns are commercially available from the Exploratorium Store in the form of plastic bags decorated with repetitive patterns, in the book *Seeing the Light* (a shimmer pattern is on page 259), in *The Moving Pattern Book*, and in the *Kaleidograph* set.

### assembly

No assembly needed.

## to do and notice \_\_\_\_\_

(15 minutes or more)

Hold two identical combs so that one is directly in front of the other and they are about a finger-width apart. Look through the teeth and notice the patterns of light and dark that appear. This is a moire pattern. Slide the combs from side to side and watch the moire pattern move. Now rotate one comb relative to the other and notice how the pattern changes.

If you only have one comb, hold it at arm's length, about 1 inch (2.5 cm) from a mirror. Look through the comb at its reflection in the mirror. Notice how the moire pattern moves when you move the comb to the side or slowly tip one end away from the mirror.

Look through two layers of window screen. Observe the moire patterns as you slide one layer from side to side across the other, or when you rotate one layer. You can also create interesting patterns by flexing one of the screens.

If you only have one piece of screen, you can still make moire patterns - even if the screen is still mounted in a window or a door. Have a friend hold a sheet of white cardboard behind the screen, and shine a single bright light onto the screen. (On a sunny day, sunshine can serve as your light source.) Start with the cardboard touching the screen, then move it away, tilting the cardboard a little as you go. The screen will form a moire pattern with its own shadow. Replace the cardboard with flexible white paper and bend the paper. Notice how the pattern changes.

Use a copy machine to make two transparencies from the pattern of concentric circles provided with this Snack as a separate page, [here](#). Look through these two patterns as you move them apart and then together. The moire pattern consists of radiating dark and light lines.

You can project moire patterns so that a large group can see them. Just make two transparencies of a repetitive pattern and overlap the transparencies on an overhead projector. Moire patterns from books may be enlarged or reduced and made into transparencies on a copy machine.

## what's going on? \_\_\_\_\_

When two identical repetitive patterns of lines, circles, or arrays of dots are overlapped with imperfect alignment, the pattern of light and dark lines that we call a *moire pattern* appears. The moire pattern is not a pattern in the screens themselves, but rather a pattern in the image formed in your eye. In some places, black lines on the front screen hide the clear lines on the rear screen, creating a dark area. Where the black lines on the front screen align with black lines on the rear, the neighboring clear areas show through, leaving a light region. The patterns formed by the regions of dark and light are moire patterns.

In the case of the two sets of concentric circular lines, the dark lines are like the nodal lines of a two-source interference pattern. A typical two-source interference pattern is created when light passes through two slits. Along lines known as *nodal lines*, the peaks of the light waves from one slit and the valleys of the light waves from the other slit overlap and cancel each other. No light is detected along a nodal line.

In the black radiating lines of the moire pattern, the black lines of one moire pattern fill the transparent lines of the other. Note that as the patterns are moved apart, the dark, nodal lines move together. This is the same thing that happens when light passes through two slits and the slits are moved farther apart.

Moire patterns magnify differences between two repetitive patterns. If two patterns are exactly lined up, then no moire pattern appears. The slightest misalignment of two patterns will create a large-scale, easily visible moire pattern. As the misalignment increases, the lines of the moire pattern will appear thinner and closer together.

## etcetera ---

Once you have learned to see moire patterns, you'll begin to see them practically everywhere. Look through two chain-link fences and notice the pattern.

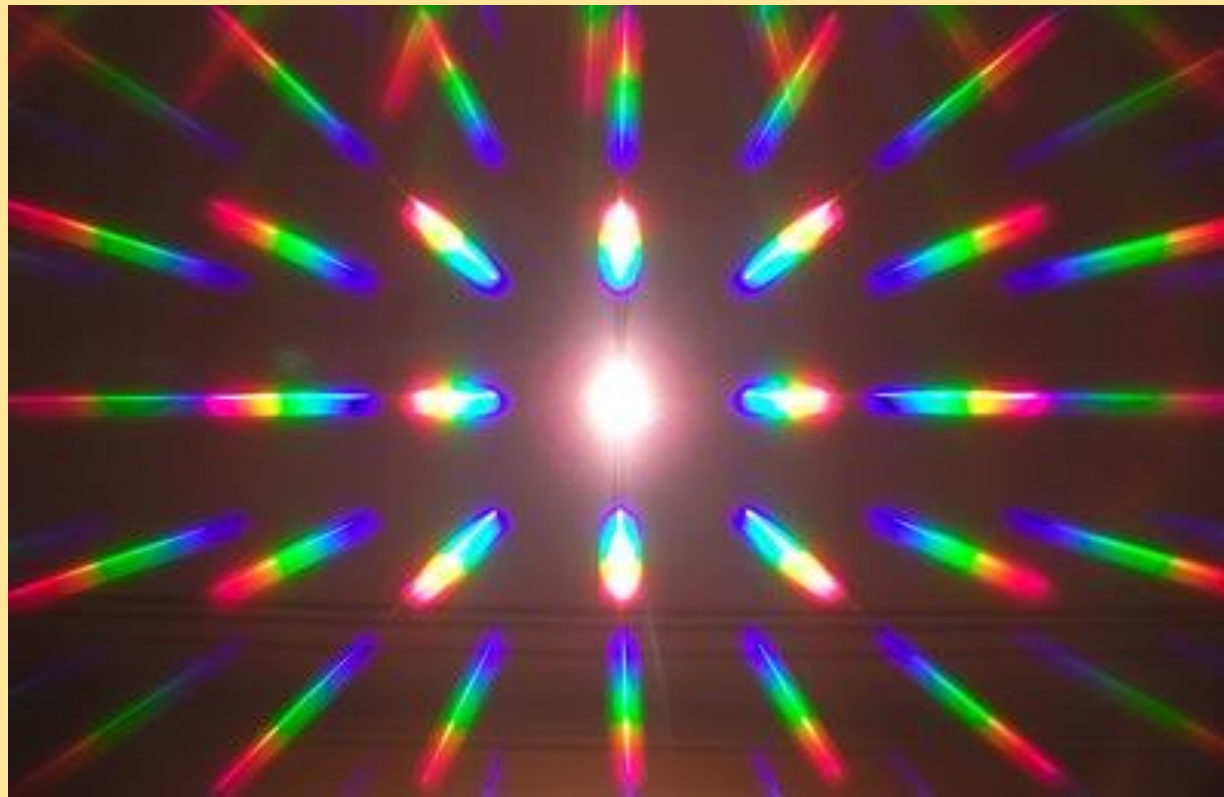
Watch it shift as you drive by. Look through a thin, finely woven fabric, such as a white handkerchief, or some pantyhose material. Now fold the fabric over and look again through two layers. You'll see moire patterns. Slide the fabric around and watch the patterns dance and change.

If your browser uses Shockwave, watch moire in motion at our [Spatial Beats](#) phenomenon page.

[Snack Home](#) | [Teacher Institute Home](#) | [Teaching Tools](#) | [Use Policy](#) | [Contact](#)  
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# DIFFRACTION OF LIGHT

Diffraction, Lasers and Holograms

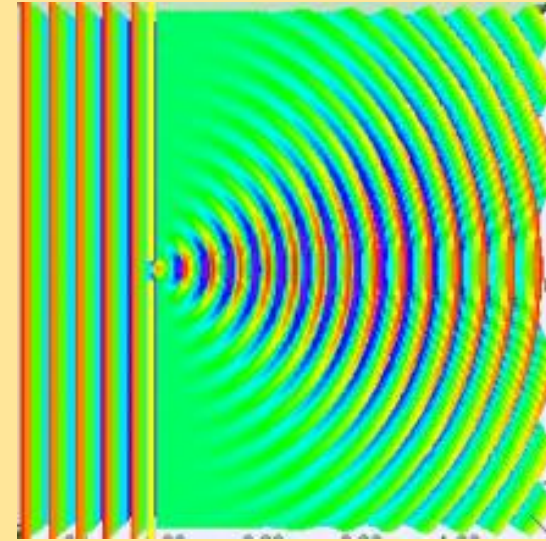


<http://dansdata.blogsome.com/2006/12/19/light-bulb-diffraction/>

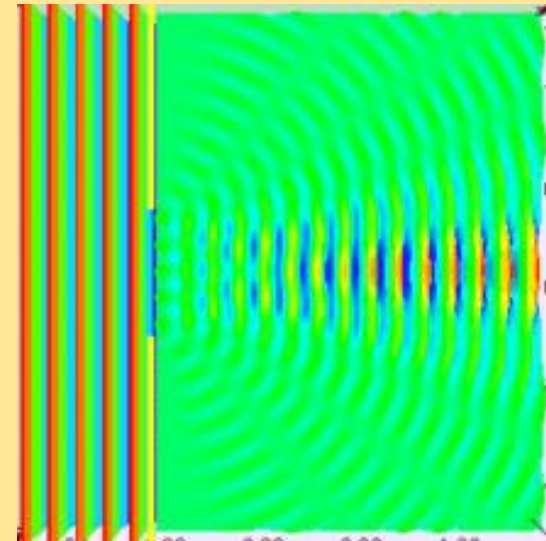
# DIFFRACTION

- Diffraction: the spreading of waves into a region behind an obstruction.
- Diffraction patterns are less spread out-and therefore less visible-when light passes through a wider slit.

This is due to the slit no longer resembles a point source. The light from broad sources is responsible for the sharp shadows produced by obstacles.

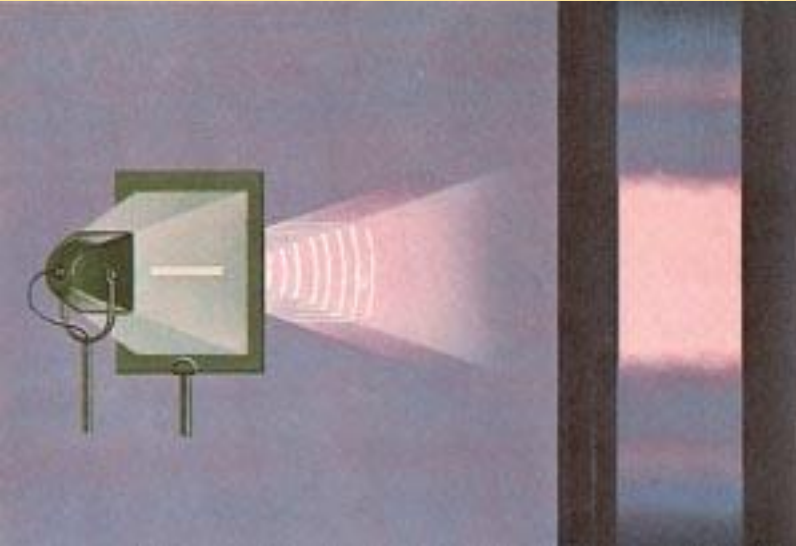


Diffraction pattern from a slit width equal to wavelength of an incident plane wave in 3D spectrum visualization

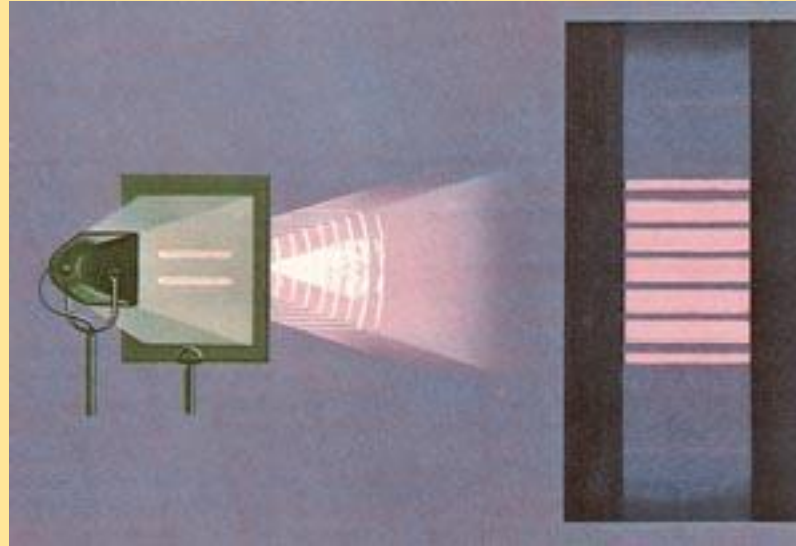


Diffraction pattern from a slit width equal to five times the wavelength of an incident plane wave in 3D spectrum visualization

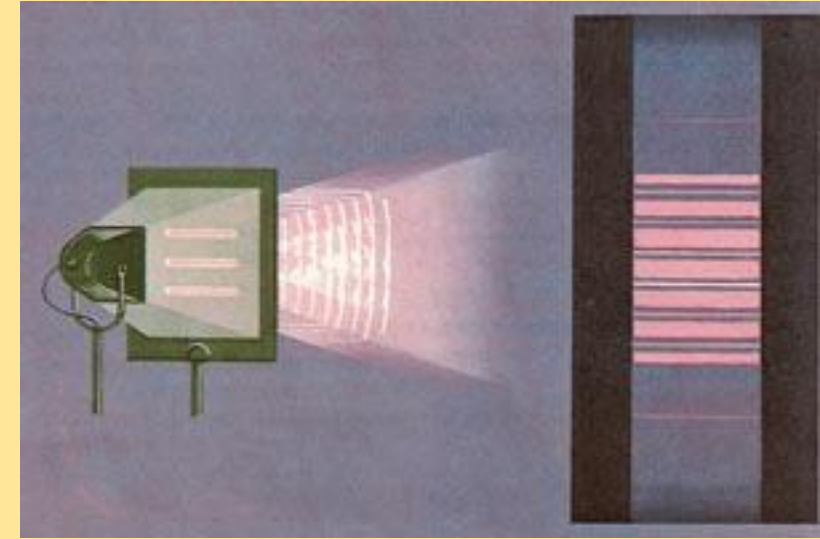
# DIFFRACTION AND INTERFERENCE



**Light spreads out, or diffracts, from the narrow slit opening, to form a diffraction pattern on the screen.**

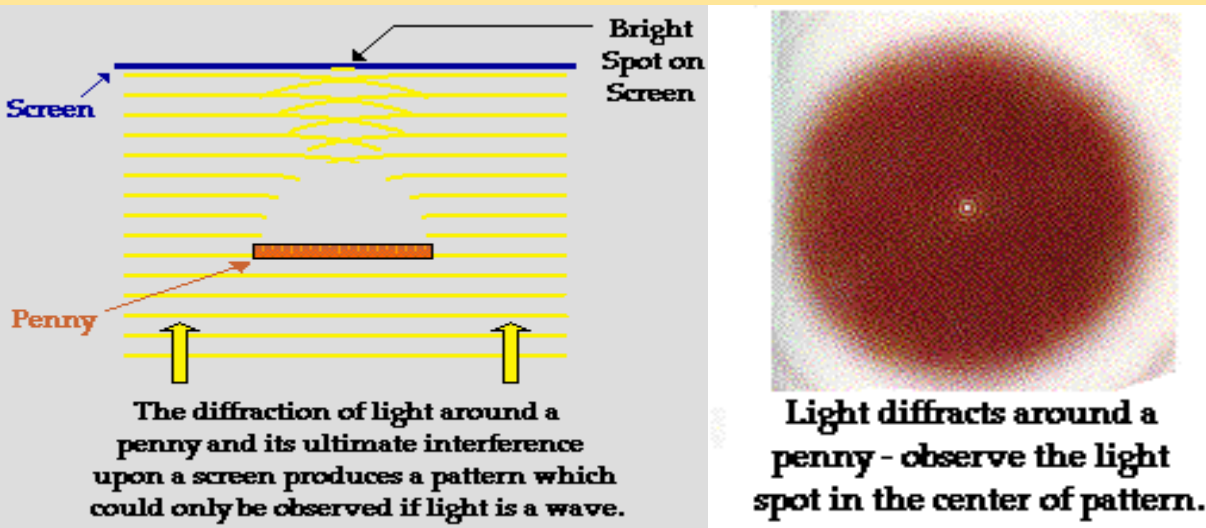


**The diffracted beams from two slits interfere to make narrow bands of light and dark, interference fringes on the screen.**

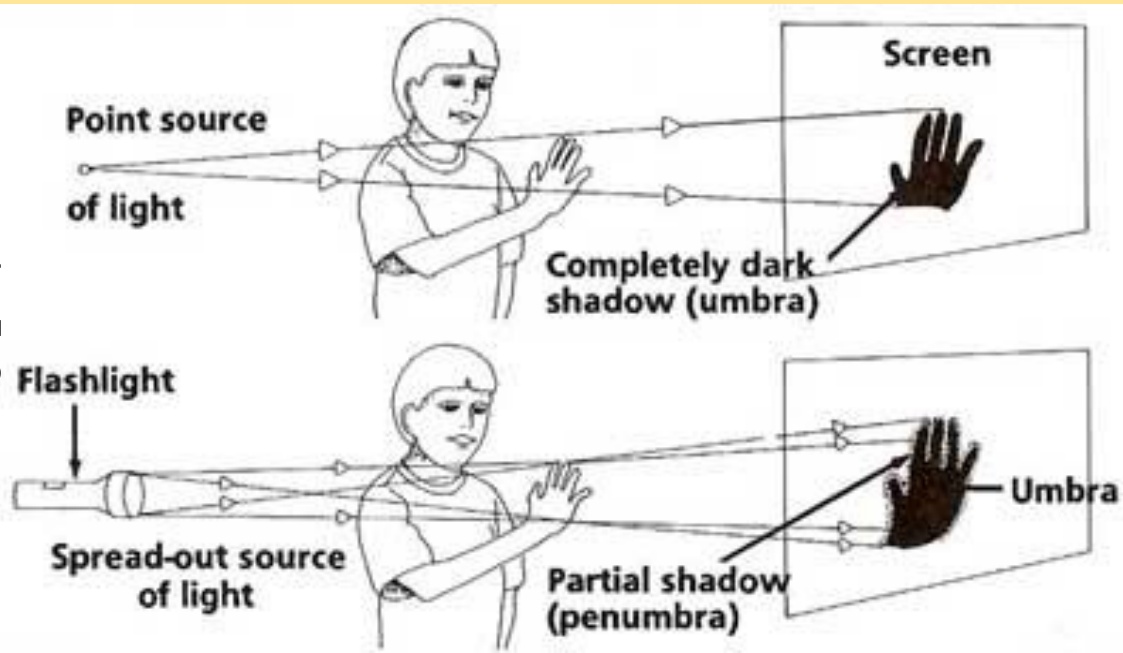


**The effect of increasing the number of slits is to narrow and brighten the bright fringes. Smaller bright fringes between the major fringes disappear as more slits are used.**

# DIFFRACTION AND SHADOWS



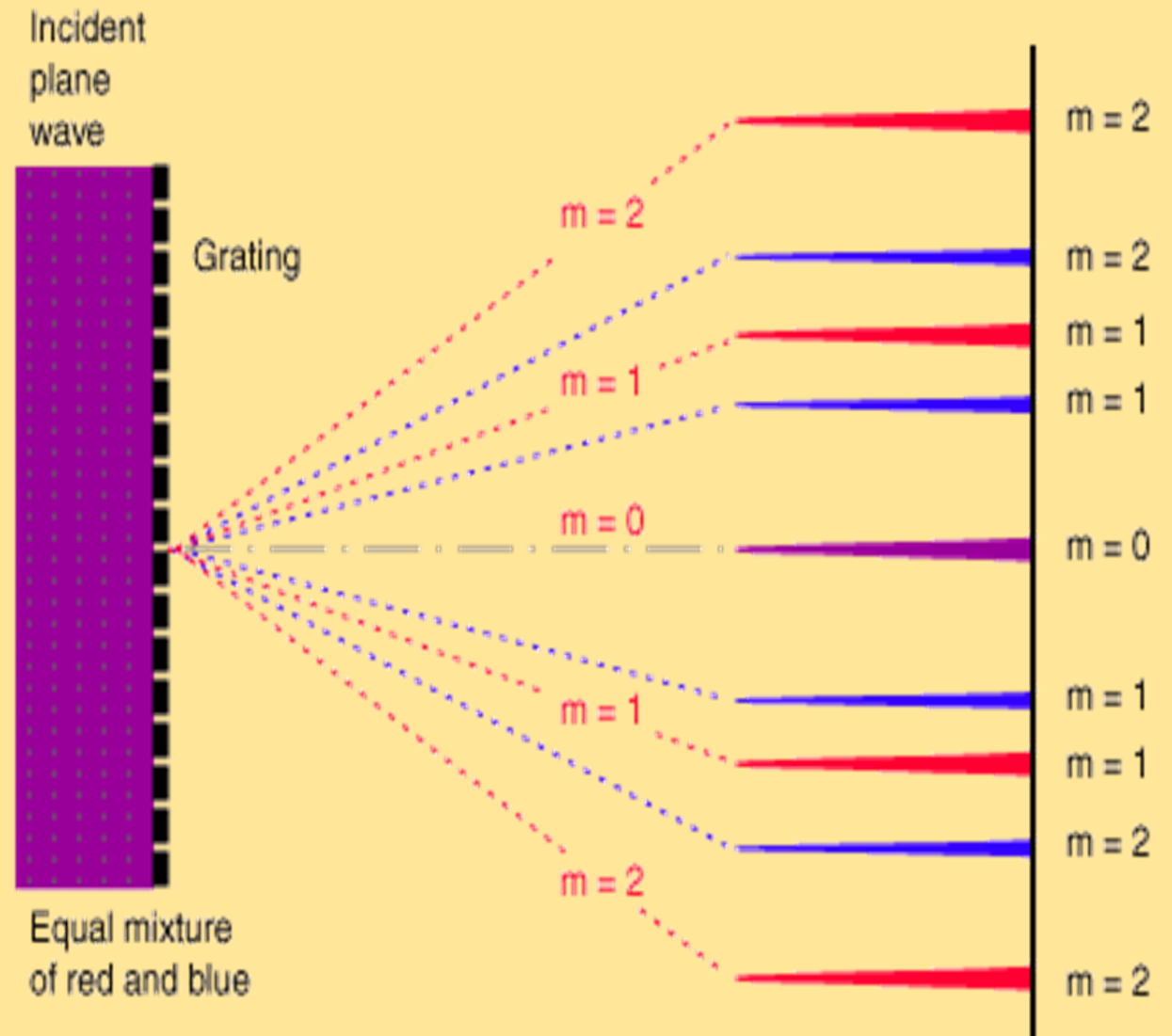
<http://www.physicsclassroom.com/Class/light/u12l1a.cfm>



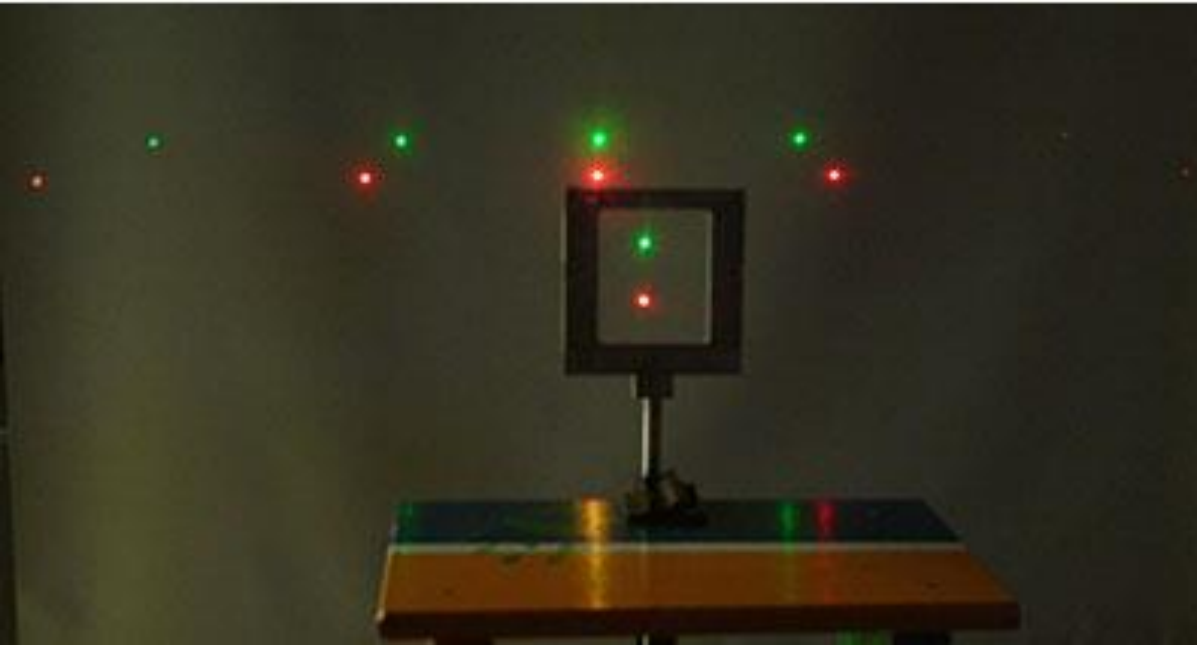
- A shadow is formed where light rays cannot reach. The light from broad sources is responsible for the sharp shadows produced by obstacles.
- Sharp shadows can be created by a small light source nearby or by larger source farther away.
- One result of diffraction is that sharp shadows are not produced due to interference.
- Usually, there is a dark part on the inside and a lighter part around the edges of the shadow.
- Umbra: a total shadow
- Penumbra: a partial shadow; it appears where some of the light is blocked.

# DIFFRACTION GRATINGS

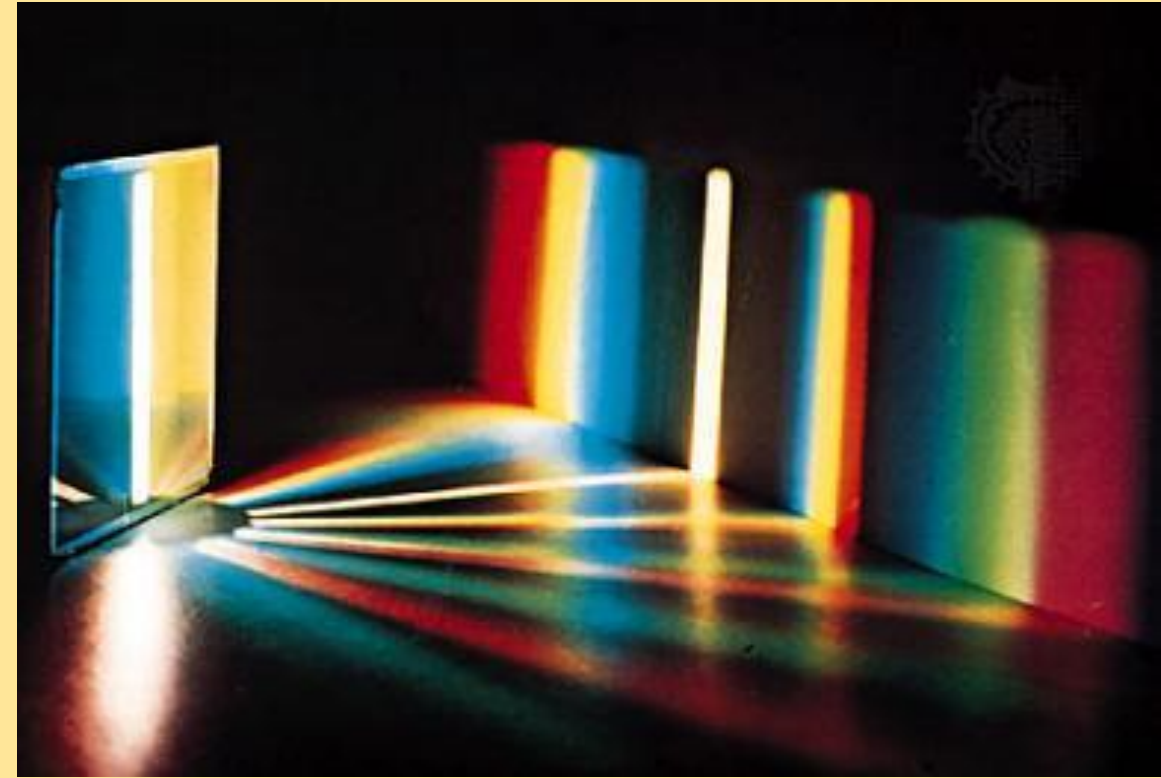
- A diffraction grating uses diffraction and interference to disperse light into its component colors with an effect similar to that of a glass prism.
- $d(\sin\theta) = m\lambda$
- $m = 0, \pm 1, \pm 2, \dots$



# Diffraction of a green and red laser.



# Diffraction of a white light source.



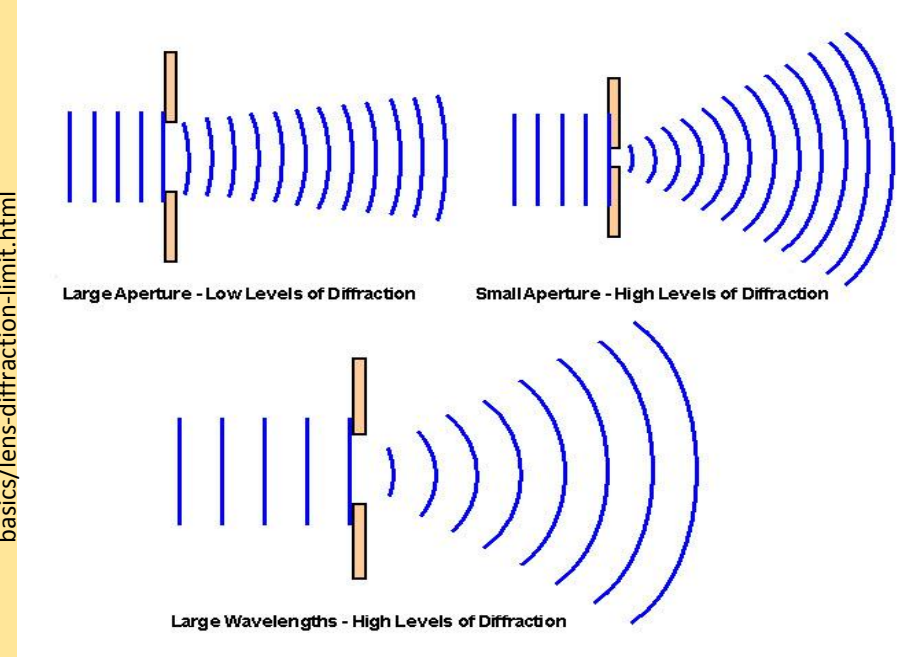
<https://wiki.brown.edu/confluence/display/PhysicsLabs/PHYS+0040+Basic+Physics>

# DIFFRACTION AND OPTICAL INSTRUMENTS

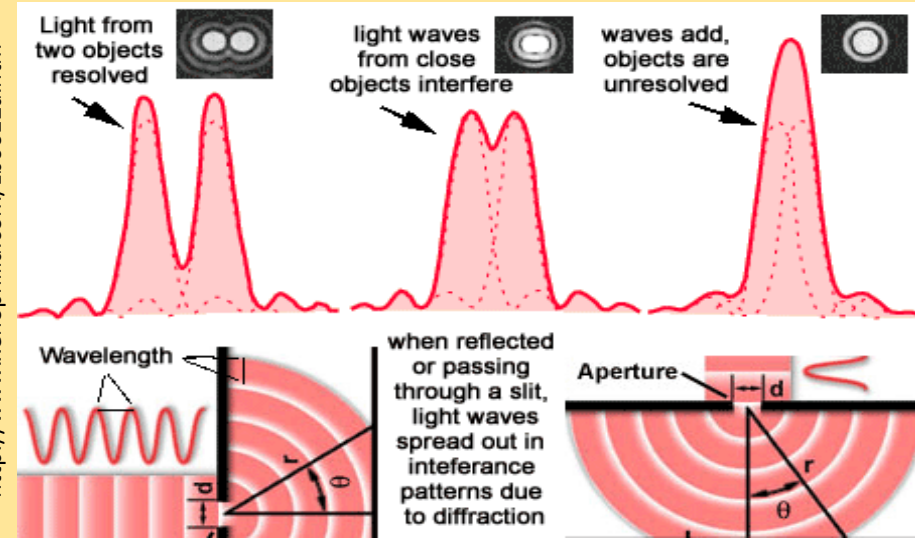
- Resolution: ability of an optical instrument to resolve detail in the object that is being imaged. It depends on wavelength and aperture width.
- The resolution of an optical instrument can be limited by factors such as flaws in the lenses or misalignment. However, there is a max to the resolution of any optical instrument due to diffraction.
- Resolving power is the ability of an optical instrument to separate two images that are close together. It is greater for short wavelengths.

$$\sin \theta = 1.22 \frac{\lambda}{D}$$

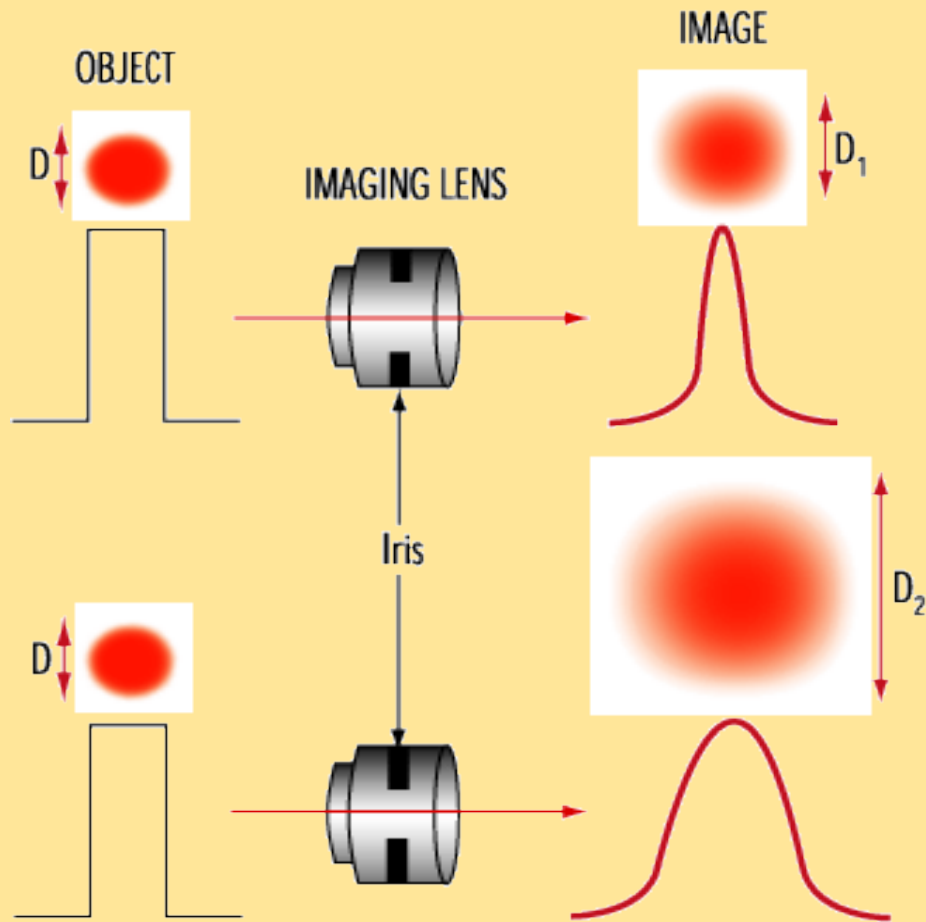
<http://www.imagen-estilo.com/Articles/Photography-basics/lens-diffraction-limit.html>



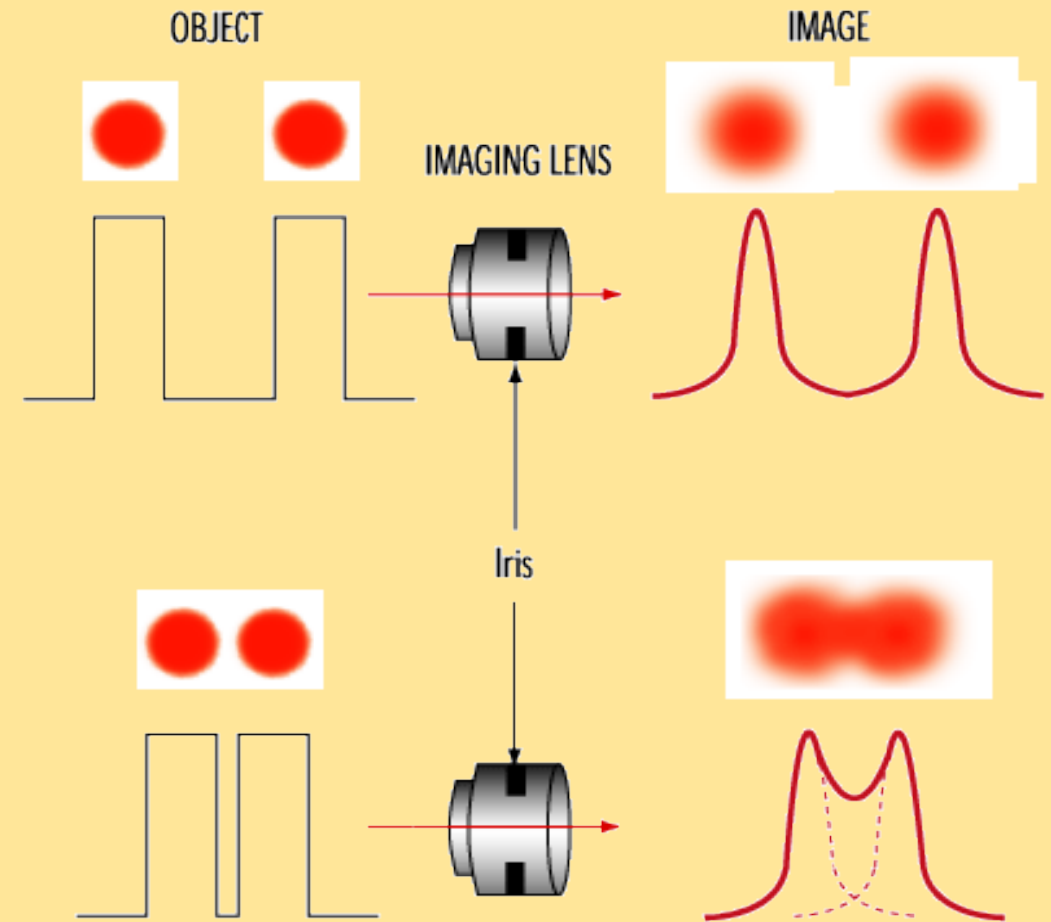
<http://www.xenophilia.com/zbo012a.htm>



# DIFFRACTION AND OPTICAL INSTRUMENTS



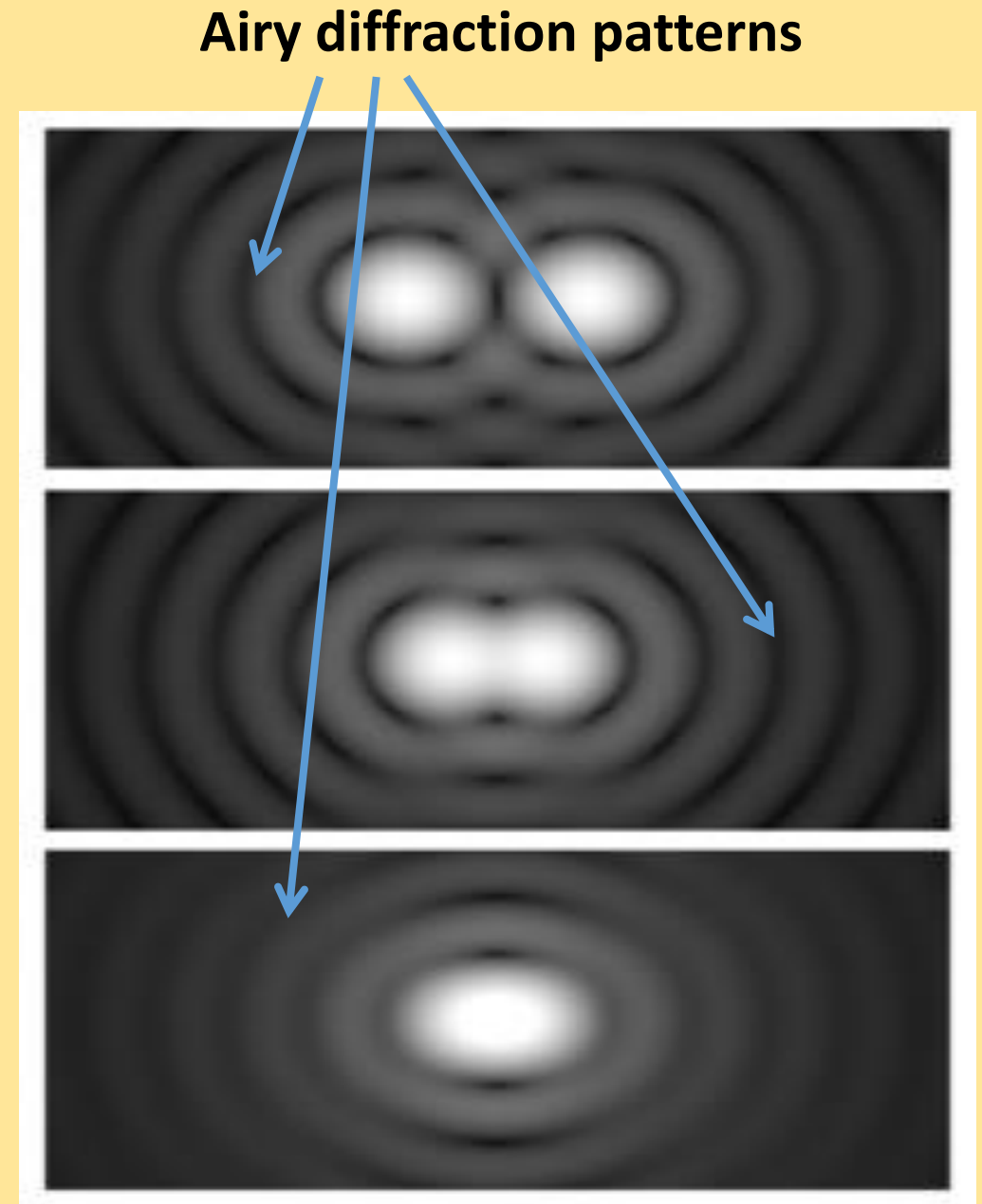
***Diffraction increases as the imaging lens iris is closed***



***Resolution/contrast decrease as the diffracted dots approach each other because they begin to blend together***

# RESOLUTION

Airy diffraction patterns generated by light from two points passing through a circular aperture, such as the pupil of the eye. Points far apart (top) or meeting the Rayleigh criterion (middle) can be distinguished. Points closer than the Rayleigh criterion (bottom) are difficult to distinguish.



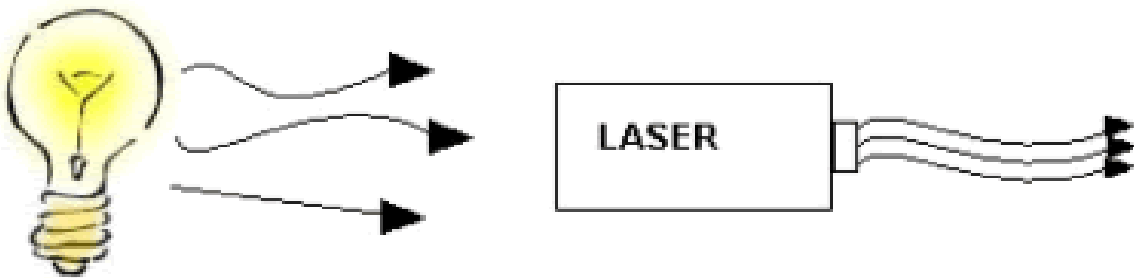
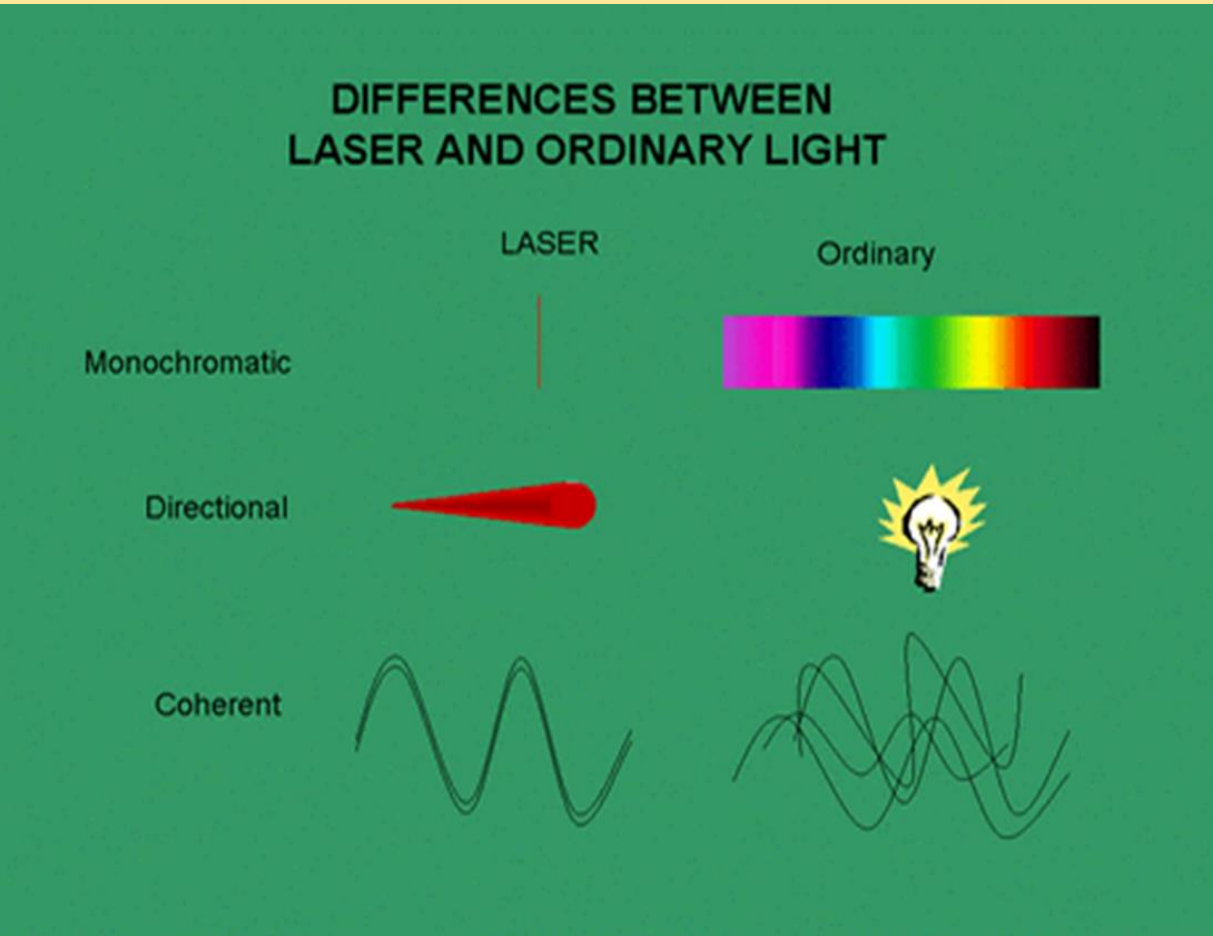
# LASERS: Light Amplification by Stimulated Emission of Radiation

- A laser is a device that converts light, electrical energy, or chemical energy into coherent light.
- There are many types of lasers but they all use an active medium to which energy is added to produce coherent light.
- The active medium can be solid, liquid, or gas. The composition of the active medium determines the wavelength, or color, of the light produced by the laser.



Red (635nm), green (532nm) and blue (445nm) laser pointers; [http://en.wikipedia.org/wiki/Laser\\_pointer](http://en.wikipedia.org/wiki/Laser_pointer)

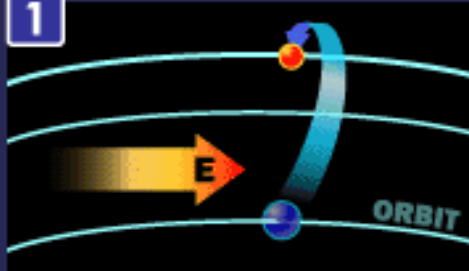
# LASERS



- Unlike incandescent light sources that emit electromagnetic waves at different times and in different directions, lasers produce an intense, nearly parallel beam of coherent light.
- Because the light waves are in phase in a laser, they interfere constructively at all points. (increases amplitude → energy)

# HOW A LASER WORKS

1



Electron is pumped to a higher energy level.

2



Pumping level is unstable, so the electron quickly jumps to a slightly lower energy level.

3



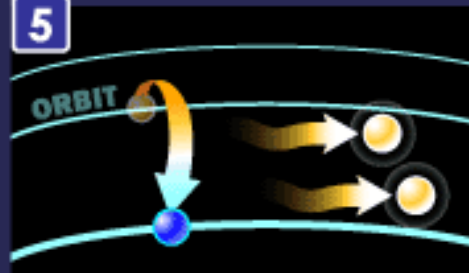
Electron relaxes to a lower energy state and releases a photon.

4



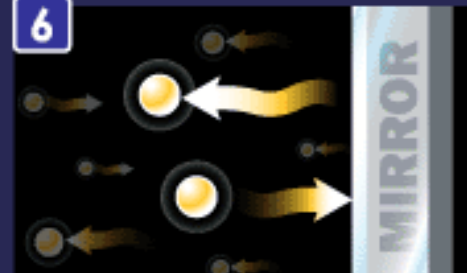
Light and an electron in an excited energy level...

5



...produces two photons of the same wavelength and phase.

6



Mirror reflects photons.

# USES OF LASERS

- A laser can measure large distances, because it can be pointed at distant reflectors and detected again.
- Lasers improve information storage and retrieval.
- Lasers are used in CD and DVD players.
- Lasers are used in medical procedures.
- Lasers are used in scientific research.



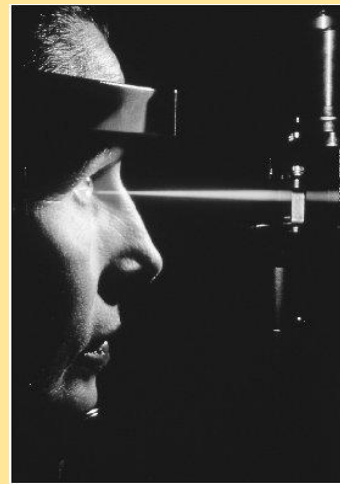
*Laser beam aimed at Moon by a telescope at McDonald Observatory.*  
(Image courtesy of McDonald Observatory.)  
[http://www.lpi.usra.edu/lunar/missions/apollo/apollo\\_15/experiments/lrr/](http://www.lpi.usra.edu/lunar/missions/apollo/apollo_15/experiments/lrr/)



<http://www.ehow.com/bar-codes/>



**The laser used in a CD player**  
Image courtesy of Petrovich9 / iStockphoto  
<http://www.scienceinschool.org/print/1159>



*A patient undergoes eye surgery performed by a laser beam. In addition to treating detached retinas, lasers can remove cataracts.*  
<http://www.scienceclarified.com/scitech/Lasers/Medical-Uses-of-Lasers.html>

[United States Air Force](http://en.wikipedia.org/wiki/Laser) laser experiment;  
<http://en.wikipedia.org/wiki/Laser>



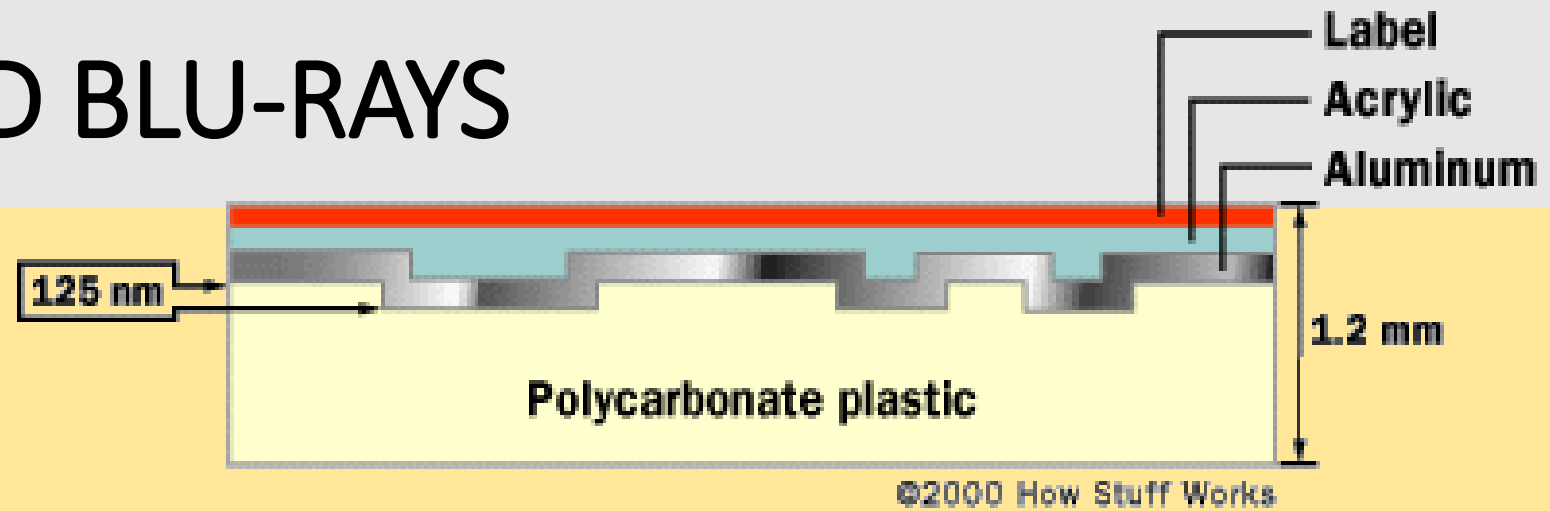
# CD/DVD RAINBOW



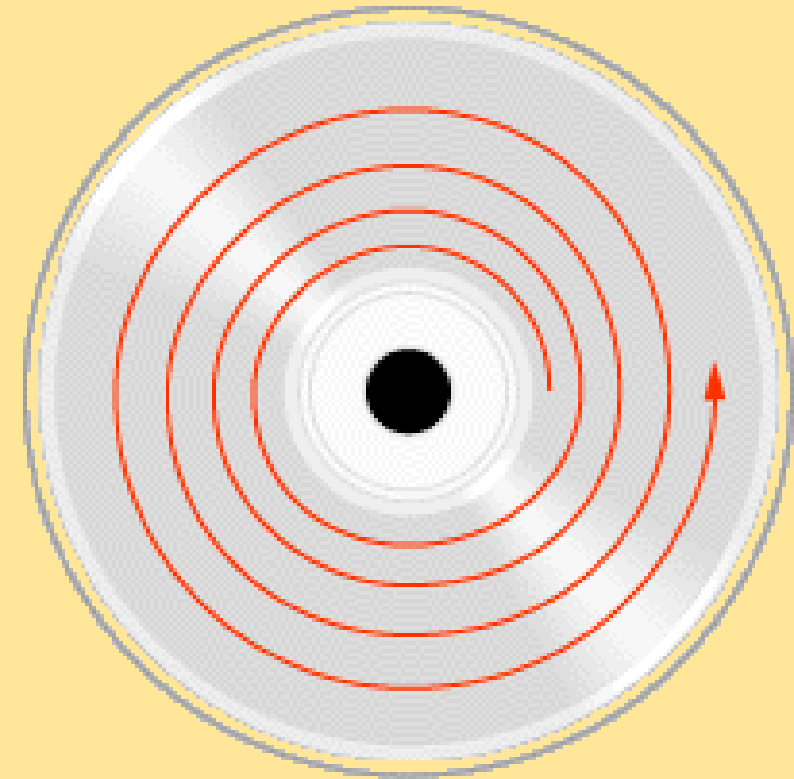
<http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/grating.html>

- If you had a **completely blank CD/DVD**, one without the spiral or spiral of bumps, it would be a **perfect mirror**. The bumps are what give a CD its rainbow colors!
- **The discs** disperse light into its component colors in a manner similar to that of a **diffraction grating**. **Constructive interference** occurs due to the various reflecting surfaces.
- Light rays bend (**diffract**) when they reflect off of the surface and separate into different wavelengths. We see each wavelength as a different color.

# CDS, DVDS AND BLU-RAYS



**A disc has a single spiral track of data, circling from the inside of the disc to the outside. The data track is approximately 0.5 microns wide, with 1.6 microns separating one track from the next.**



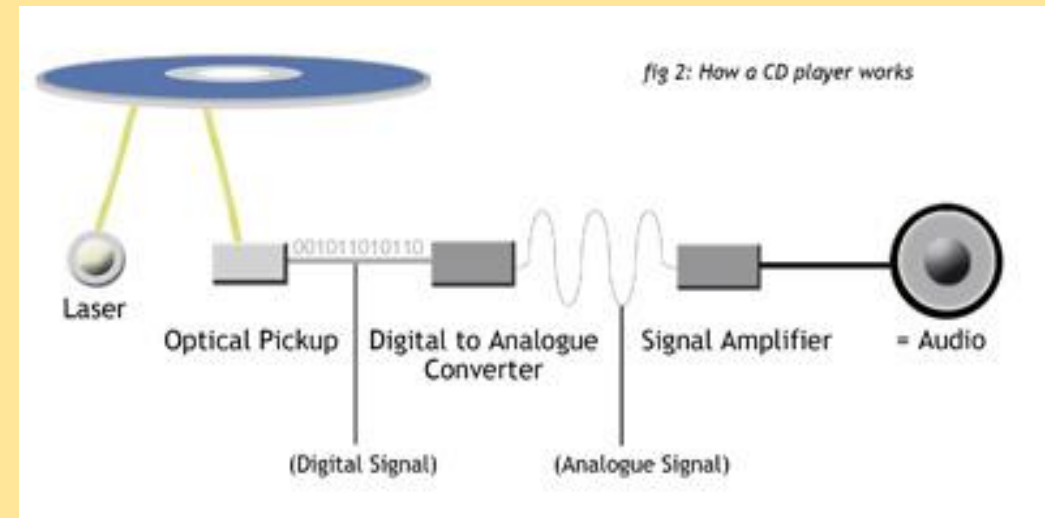
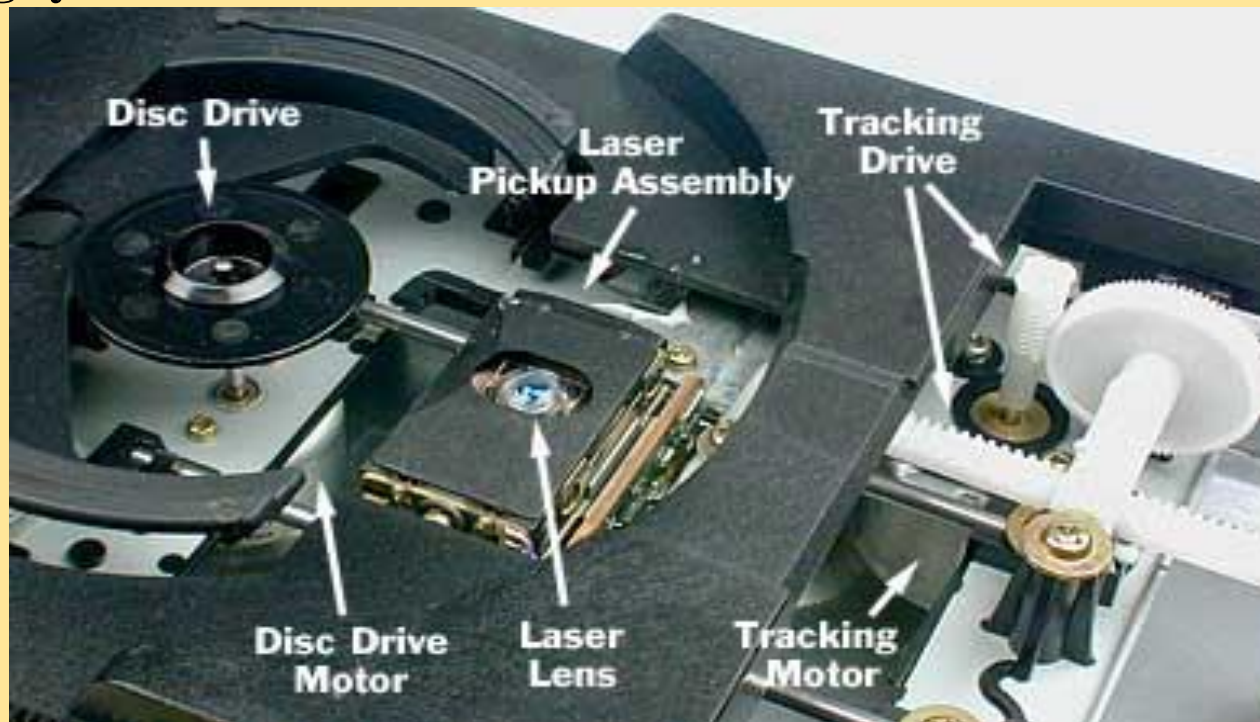
# CD/DVD Player Components

The CD/DVD player has the job of finding and reading the data stored as bumps on the disc. Considering how small the bumps are, the disc player is an exceptionally precise piece of equipment. The drive consists of three fundamental components:

A drive motor spins the disc. This drive motor is precisely controlled to rotate between 200 and 500 rpm depending on which track is being read.

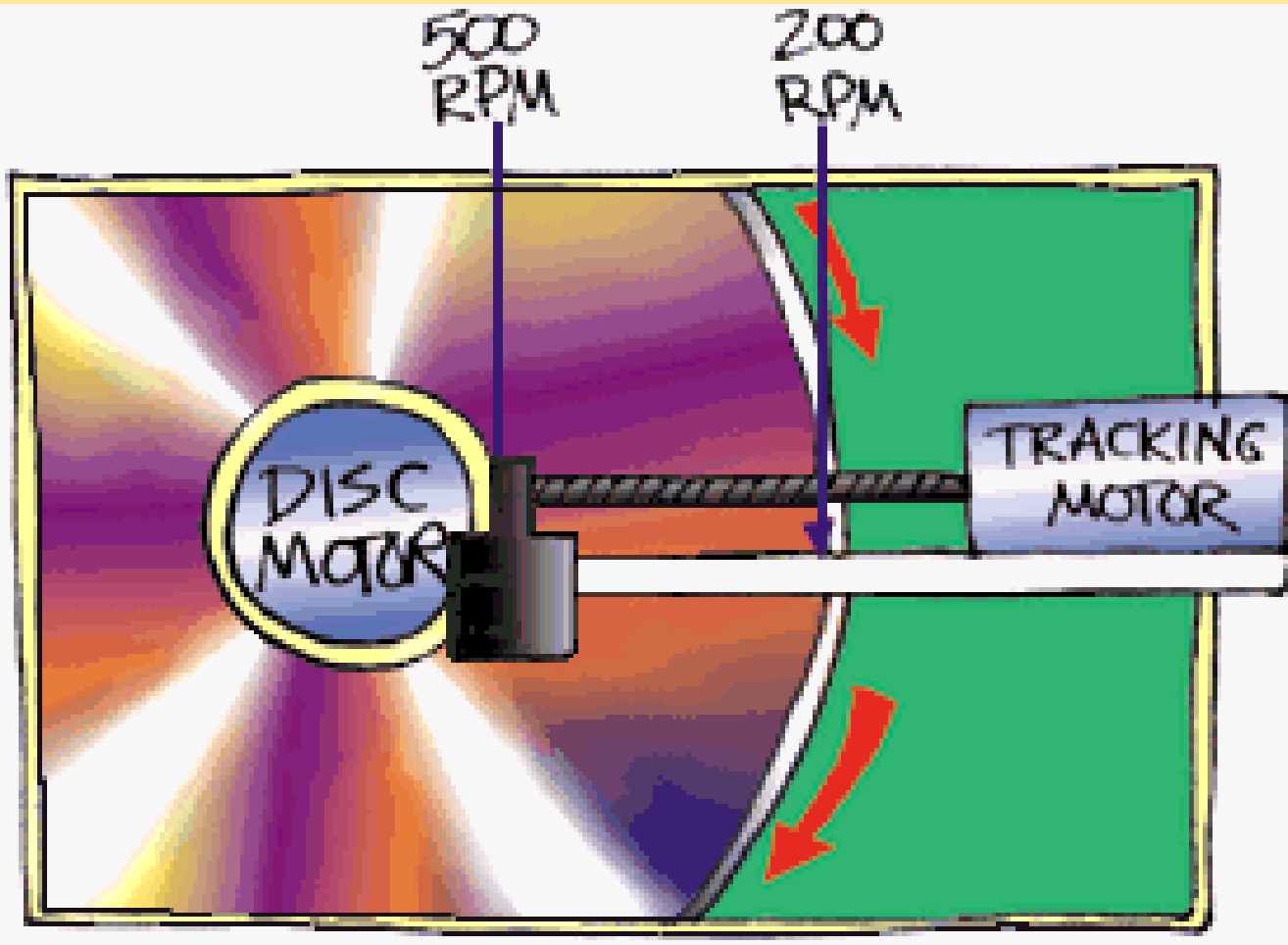
A laser and a lens system focus in on and read the bumps.

A tracking mechanism moves the laser assembly so that the laser's beam can follow the spiral track. The tracking system has to be able to move the laser at micron resolutions.



[http://www.stebbing.co.nz/resource\\_pages/cddvdworks.html](http://www.stebbing.co.nz/resource_pages/cddvdworks.html)

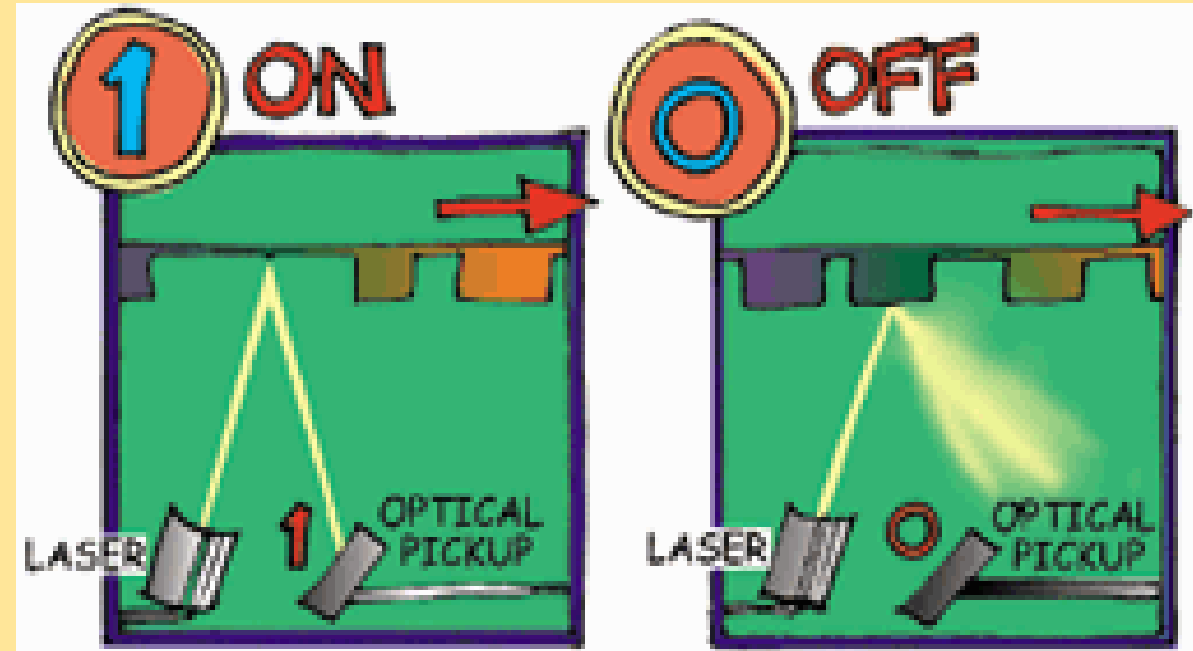
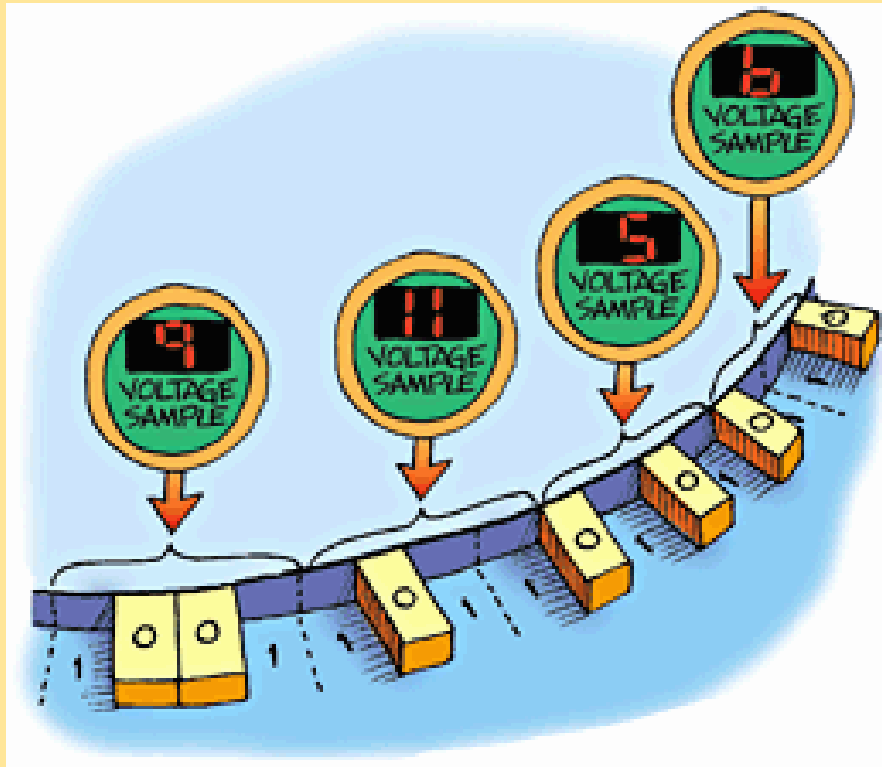
# TRACKING SYSTEM



The tracking system, as it plays the CD/DVD, has to continually move the laser outward. As the laser moves outward from the center of the disc, the bumps move past the laser faster -- this happens because the linear speed of the bumps is equal to the radius times the speed at which the disc is revolving (rpm). Therefore, as the laser moves outward, the spindle motor must slow the speed of the CD. That way, the bumps travel past the laser at a constant speed, and the data comes off the disc at a constant rate.

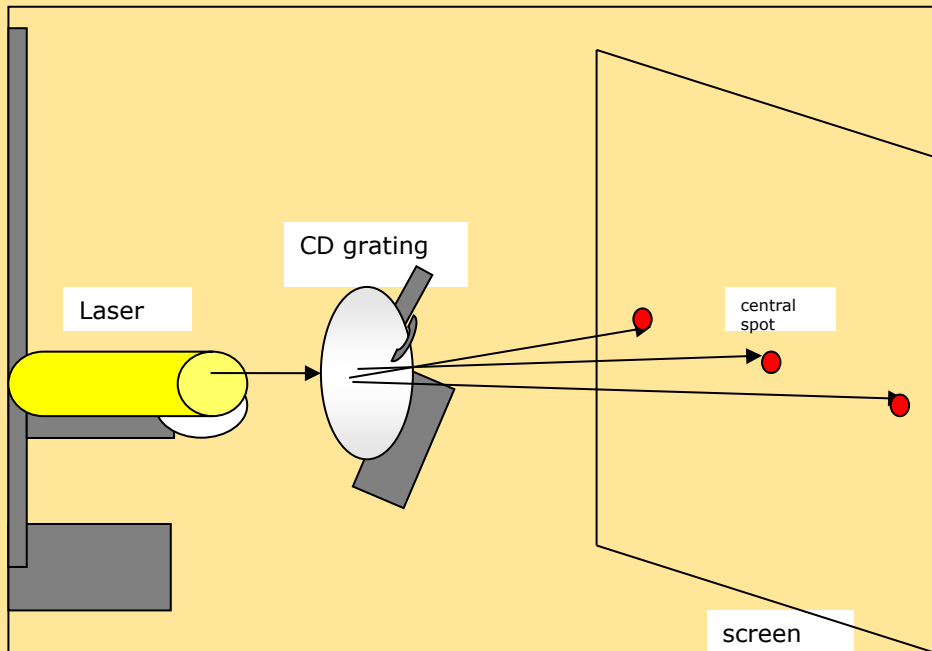
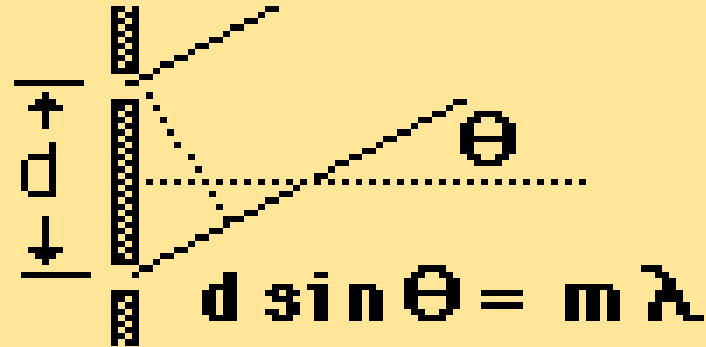
# DATA RETRIEVAL OF A CD/DVD

The laser focuses on the track of data bumps and shoots the laser beam through the polycarbonate layer so that it reflects off the aluminum layer. The reflected light activates a special on/off switch, called an opto-electronic switch. This then takes in the binary information and translates it into an audio format.



In the CD/DVD player, each string of 1s and 0s corresponds to an electrical signal (a voltage). The DAC (digital-to-analog converter) turns the numbers into voltages. The voltages change 44,000 times per second! The amplifier sends the voltages to the speakers where they turn into a series of sounds. Voltage samples (base-10 value) from 4-bit codes

# USING A CD/DVD AS A DIFFRACTION GRATING

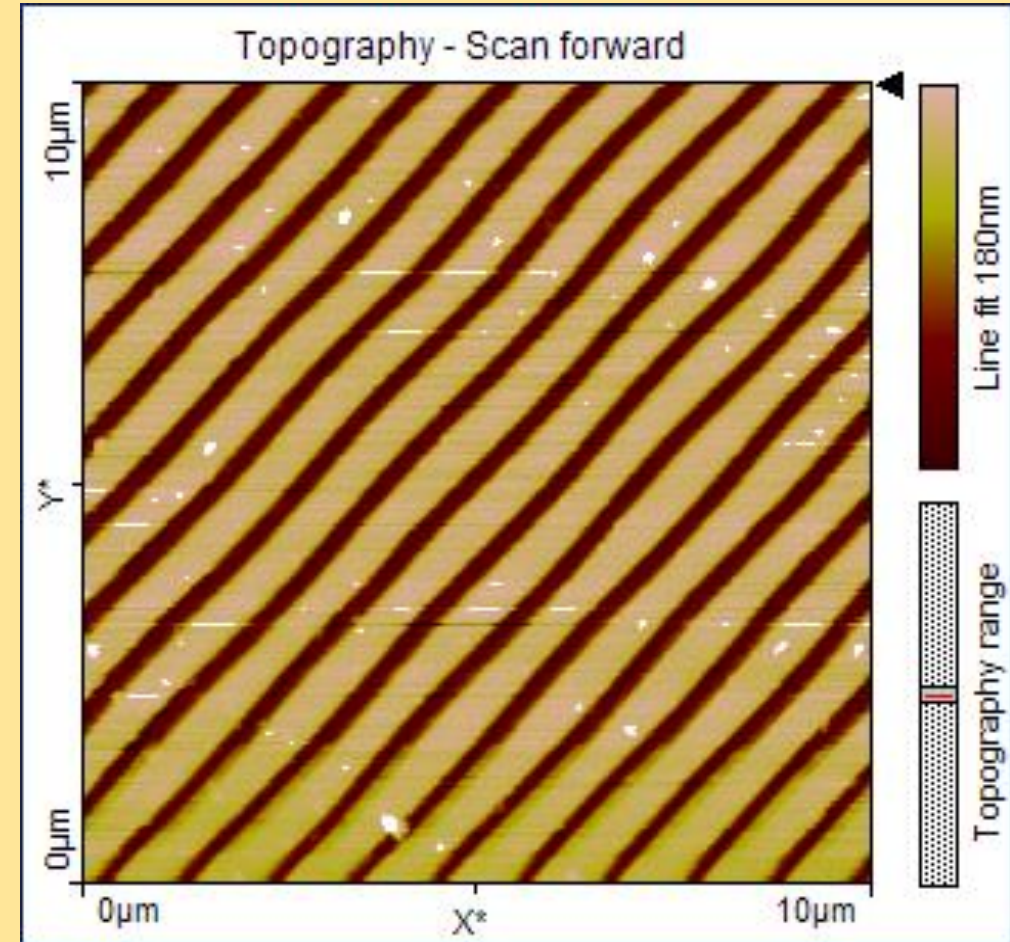
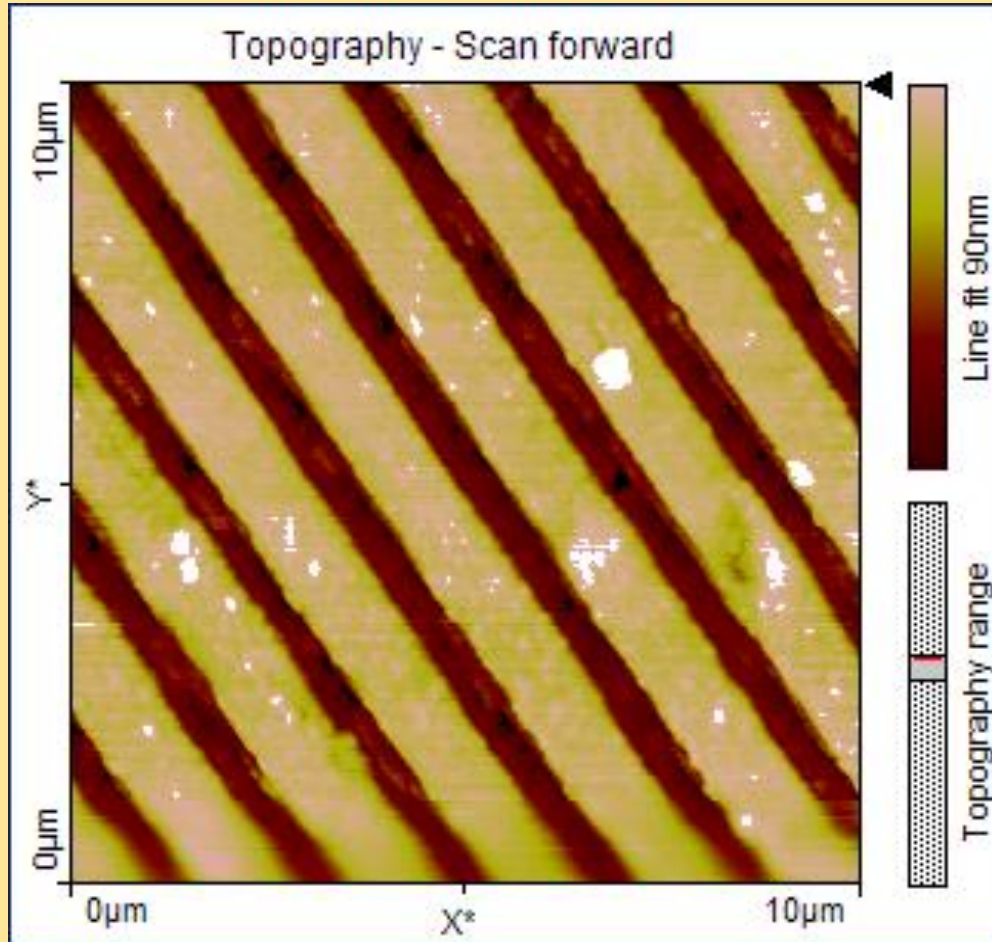


<http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/grating.html>



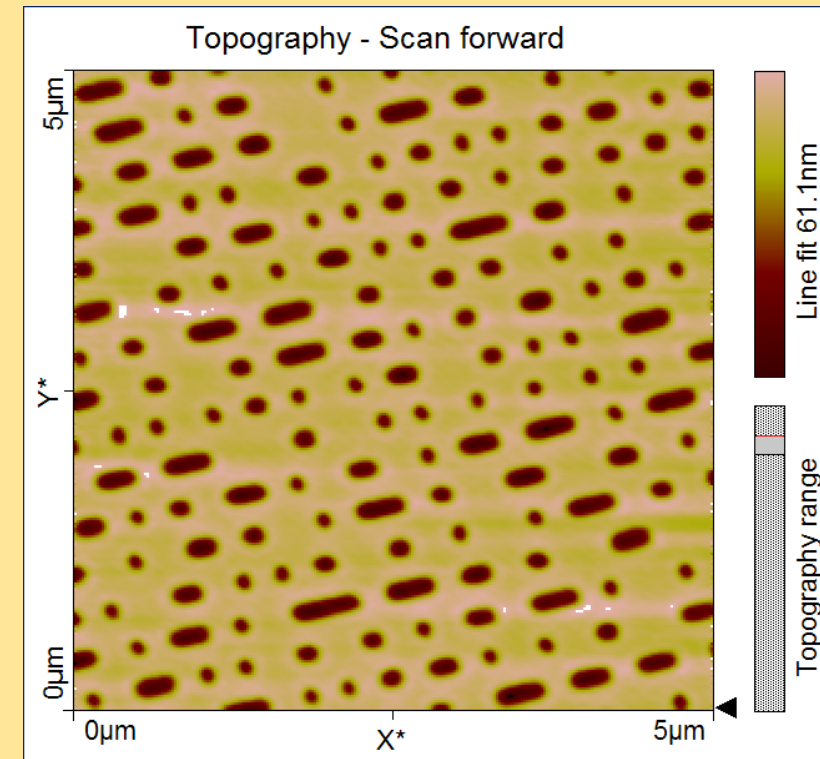
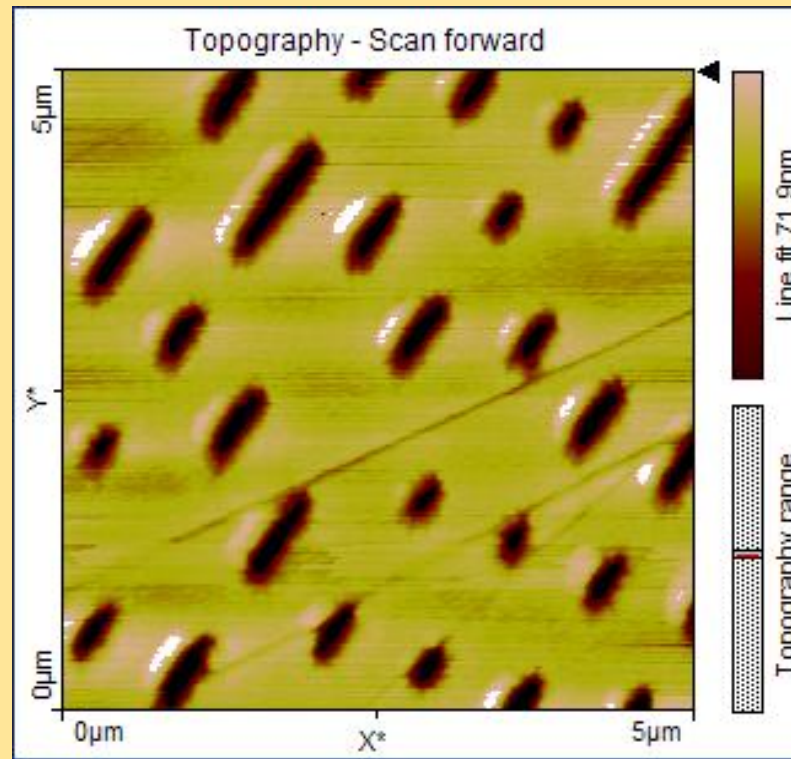
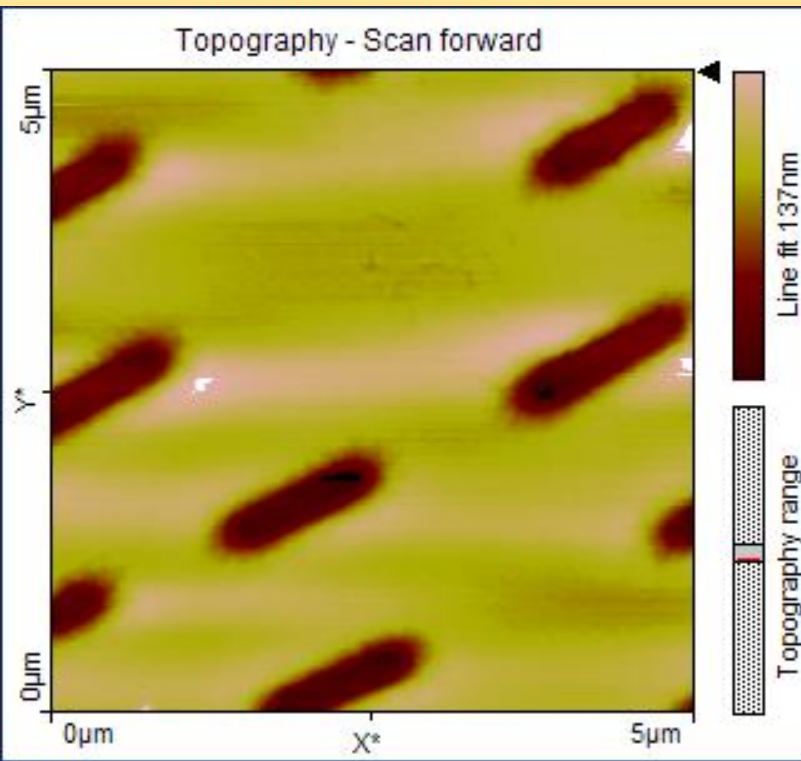
Photograph taken by Porter-Davis and Balachandran at Georgia Tech (Summer 2008)

# AFM Images of CD/DVD (unrecorded)



**Images taken by Porter-Davis and Balachandran at Georgia Tech (Summer 2008)  
on portable AFM (NNIN)**

# AFM IMAGES OF RECORDED CD, DVD AND BLU-RAY

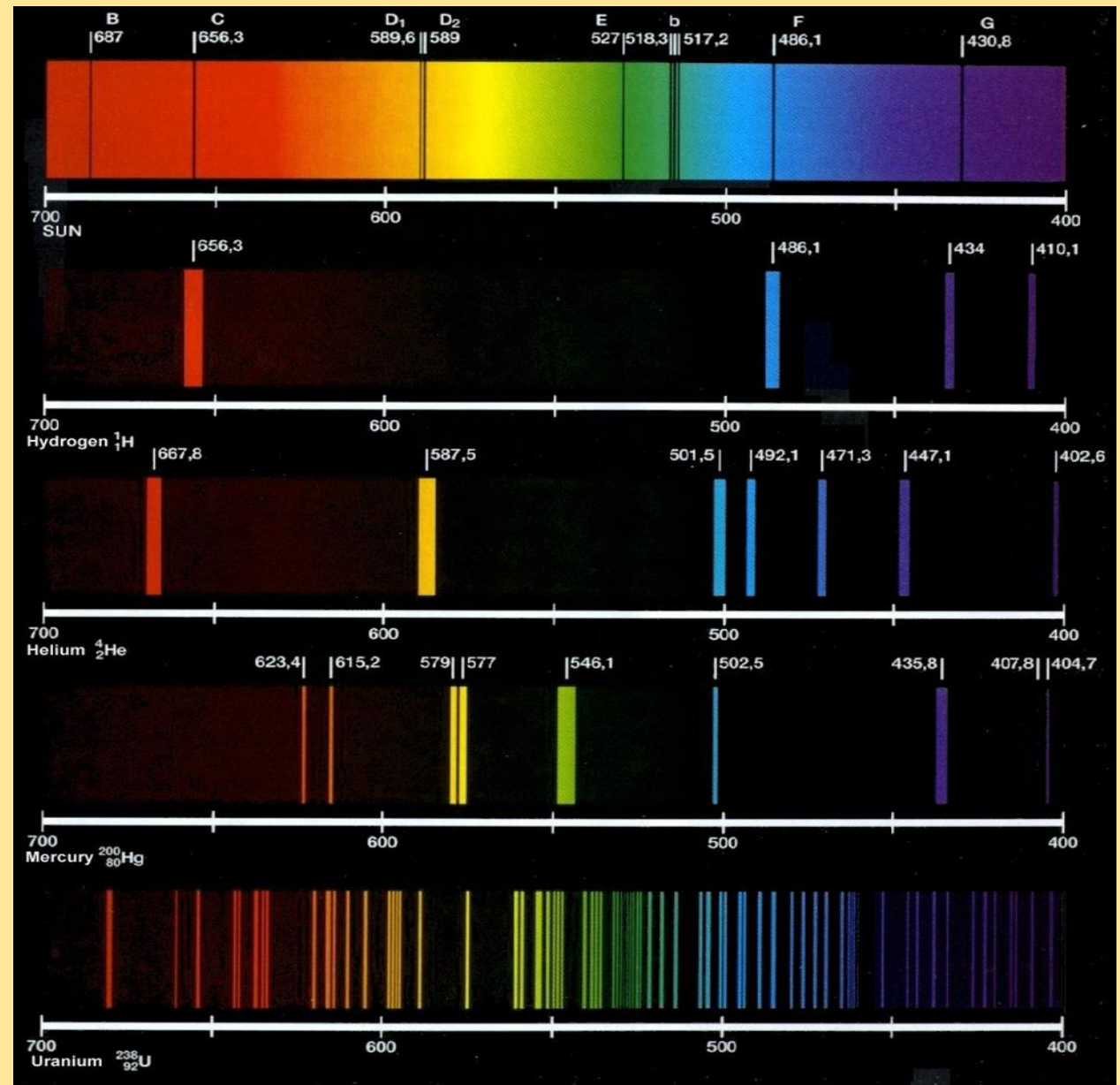


Why is it called a Blu-ray?

Images taken by Porter-Davis and Balachandran at Georgia Tech (Summer 2008) on portable AFM (NNIN)

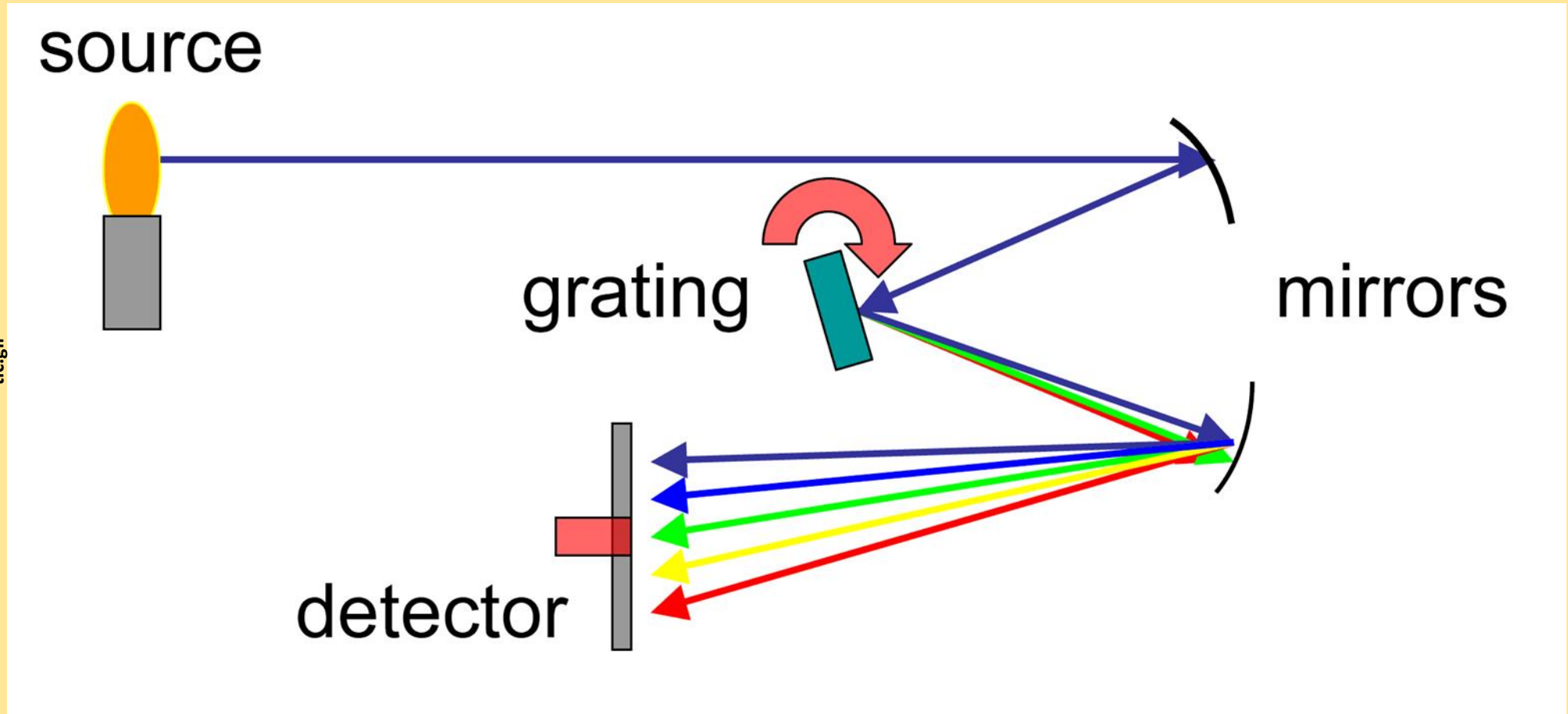
# SPECTROMETERS

- Every substance produces different light frequencies and patterns which act like a chemical fingerprint.
- Using this idea, unknown samples can be analyzed using spectrometers then compared to known patterns to determine the sample's make-up.



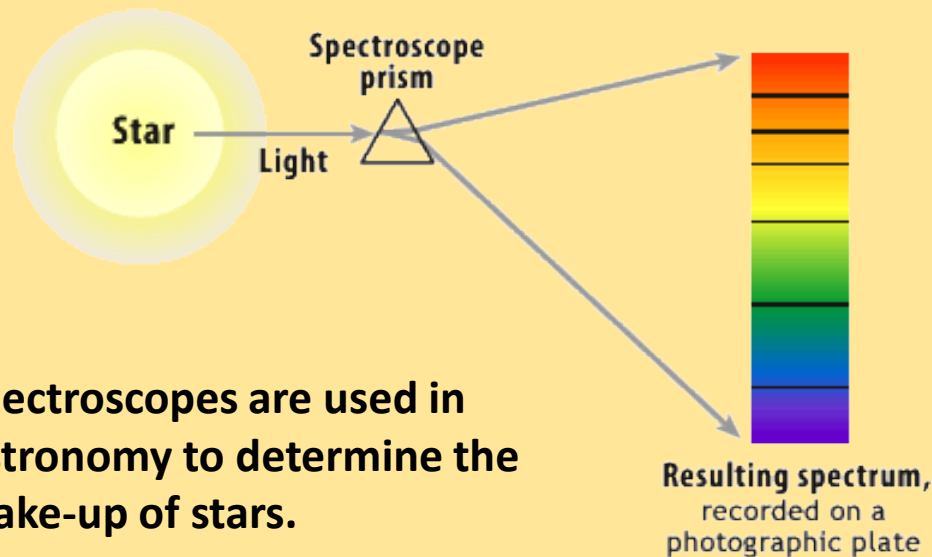
# HOW SPECTROMETERS WORK

- A simple device that begins with a way of collecting light from a sample and guiding that light onto a diffraction grating. The diffraction grating then directs light onto mirrors, which lead the light to either a flat surface to show the spectrum or a charged coupled device (CCD) chip, which can record the light pattern.



# TYPES OF SPECTROMETERS

- **Spectroscope**: uses a diffraction grating to separate electromagnetic radiation (light) into its component wavelengths. The spectroscope can be used to measure absorption or emission spectra.



Spectroscopes are used in Astronomy to determine the make-up of stars.

<http://amazing-space.stsci.edu/resources/explorations/groundup/lesson/basics/g23/>

Simple Spectroscope

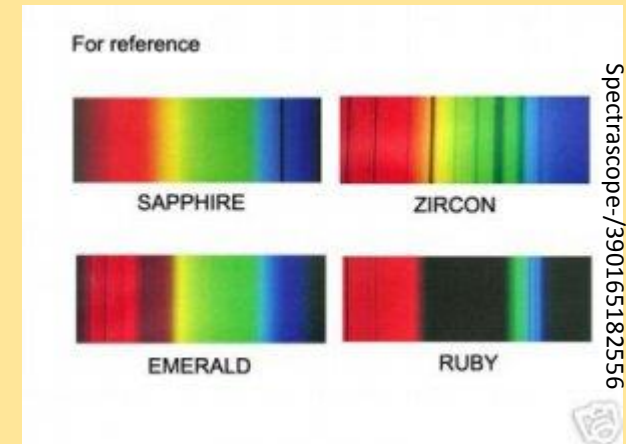


<http://www.amazon.com/Envision-Quantitative-Analysis-Spectroscope/dp/B0027UNRHY>

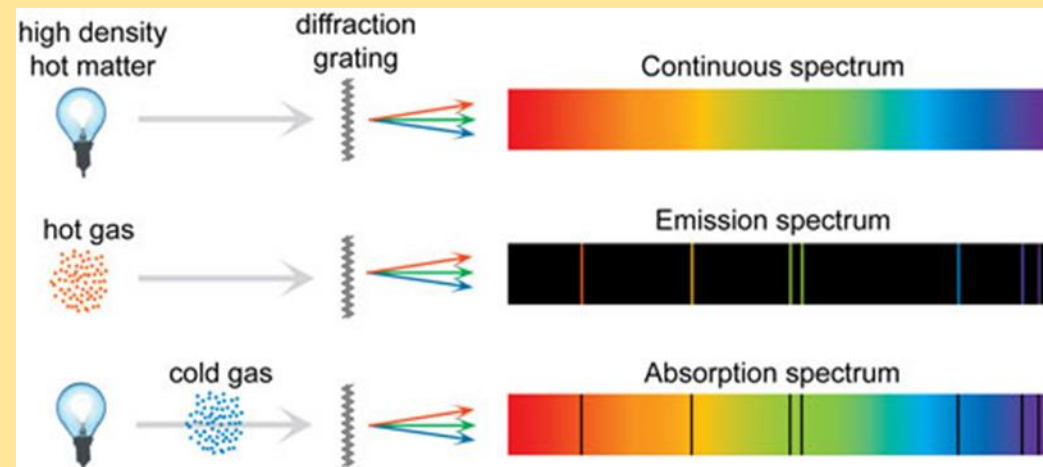


Used for Gemology

<http://gemologyproject.com/wiki/index.php?title=Spectroscope>



<http://www.ebay.com/itm/GEM-Gemstone-Diffraction-Spectroscope-Spectroscope-/390165182556>

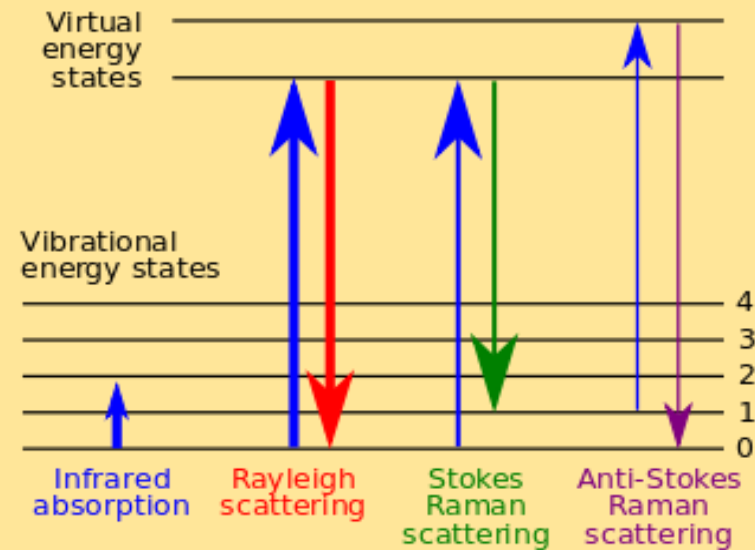


[http://www.scienceschool.org/repository/images/issue4spectrometer11\\_lar ge.jpg](http://www.scienceschool.org/repository/images/issue4spectrometer11_lar ge.jpg)

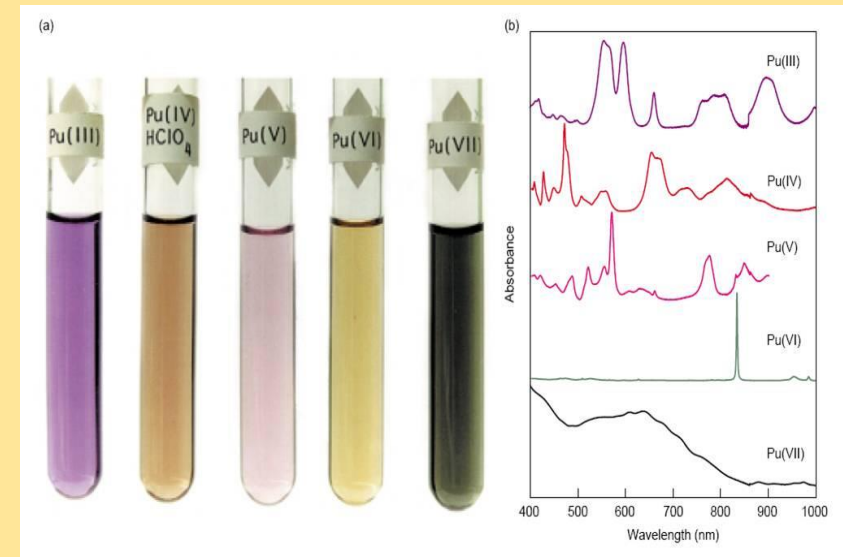
<http://www.uwplatt.edu/chemep/chem/chemscape/labdocs/catofp/measurep/spectro/spectrs3.htm>

# TYPES OF SPECTROMETERS

- **Raman Spectroscopy**: a technique used to detect vibrational, rotational and other low frequency modes in a sample.
- Based on Raman scattering which is an inelastic scattering (KE is not conserved) of a photon.
- The photon is the incident particle and interacts with matter and the frequency of the photon is shifted to red (energy of photon decreases) or blue (energy of photon increases).
- The molecular bonds and chemical make-up determine the Raman shift and spectra.



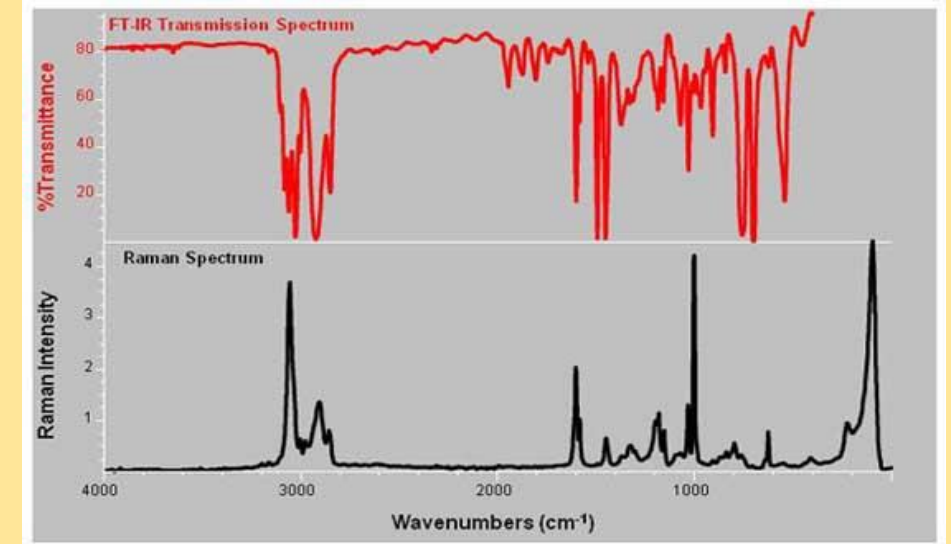
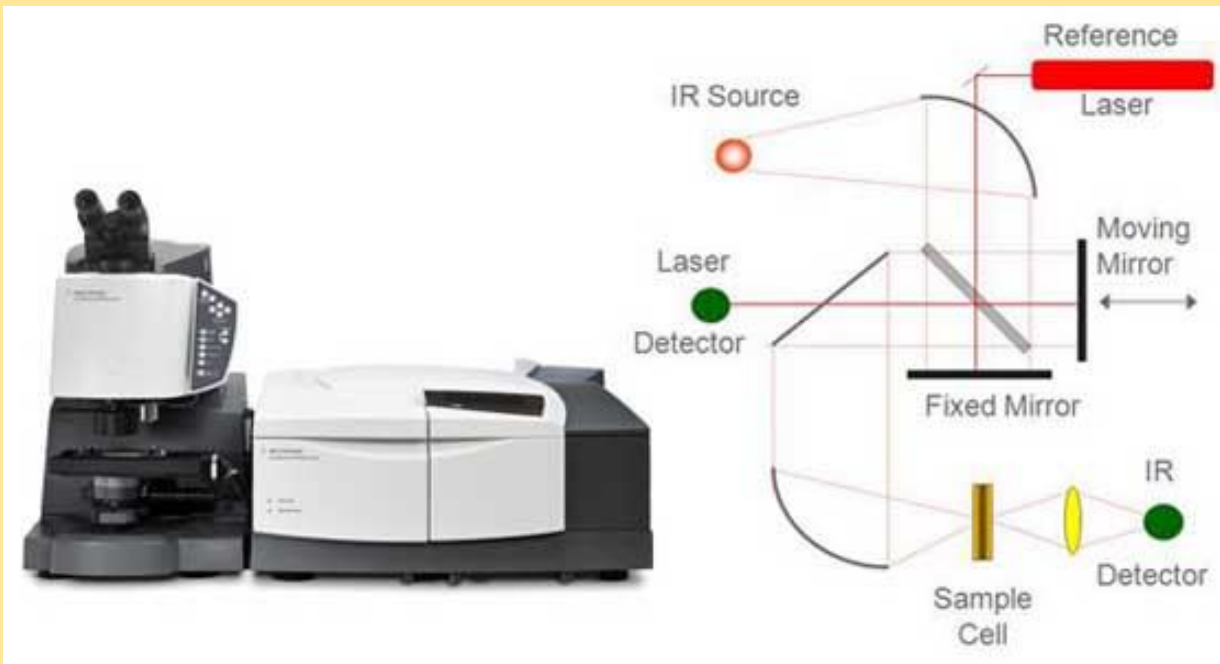
[http://en.wikipedia.org/wiki/Raman\\_transition](http://en.wikipedia.org/wiki/Raman_transition)



<http://radchem.nevada.edu/classes/chem793/lecture%204%20orbitals%20and%20energetics.html>

# TYPES OF SPECTROMETERS

- **Fourier Transform Infrared Spectroscopy (FTIR)**: is a technique which is used to interpret an infrared spectrum of absorption, emission or Raman scattering of a sample. The FTIR gathers spectral data in a wide range at the same time and then the computer takes the data to infer the absorption at each wavelength.



Raman and FTIR are complementary to one another. They both detect changes in vibration and rotation at the molecular level. But while FTIR measures the amount of IR light absorbed, Raman measures the amount of light scattered.

# NSS: PHYSICAL SCIENCE

- **MOTIONS AND FORCES**
- Gravitation is a universal force that each mass exerts on any other mass. The strength of the gravitational attractive force between two masses is proportional to the masses and inversely proportional to the square of the distance between them.
- **CONSERVATION OF ENERGY AND THE INCREASE IN DISORDER**
- All energy can be considered to be either kinetic energy, which is the energy of motion; potential energy, which depends on relative position; or energy contained by a field, such as electromagnetic waves.
- **INTERACTIONS OF ENERGY AND MATTER**
- Waves, including sound and seismic waves, waves on water, and light waves, have energy and can transfer energy when they interact with matter
- Electromagnetic waves result when a charged object is accelerated or decelerated. Electromagnetic waves include radio waves (the longest wavelength), microwaves, infrared radiation (radiant heat), visible light, ultraviolet radiation, x-rays, and gamma rays. The energy of electromagnetic waves is carried in packets whose magnitude is inversely proportional to the wavelength.
- Each kind of atom or molecule can gain or lose energy only in particular discrete amounts and thus can absorb and emit light only at wavelengths corresponding to these amounts. These wavelengths can be used to identify the substance.

# GPS: PHYSICS

## **SP4. Students will analyze the properties and applications of waves.**

- a. Explain the processes that results in the production and energy transfer of electromagnetic waves.
- b. Experimentally determine the behavior of waves in various media in terms of reflection, refraction, and diffraction of waves.
- c. Explain the relationship between the phenomena of interference and the principle of superposition.
- e. Determine the location and nature of images formed by the reflection or refraction of light.

## **SP3. Students will evaluate the forms and transformations of energy.**

- a. Analyze, evaluate, and apply the principle of conservation of energy and measure the components of work-energy theorem by
  - • describing total energy in a closed system.
  - • identifying different types of potential energy.
  - • calculating kinetic energy given mass and velocity.
  - • relating transformations between potential and kinetic energy.
- b. Explain the relationship between matter and energy.
- e. Demonstrate the factors required to produce a change in momentum.

# REFERENCES

## Books:

Serway, Raymond A., and Jerry S. Faughn. Holt Physics. Austin, Texas: Holt, Rinehart and Winston, 2000.

White, Mary Anne. Properties of Materials. New York, New York: Oxford University Press, 1999.

## Websites:

“Agilent 101: An Introduction to Optical Spectroscopy” by Andrew Hind © *Agilent 2000-2013*, April 2011. *Web*. 11 June 2013. [http://www.agilent.com/labs/features/2011\\_101\\_spectroscopy.html](http://www.agilent.com/labs/features/2011_101_spectroscopy.html)

“Anti-Reflective Coating” *Wikipedia* Wikimedia Foundation, Inc. 1 June 2011 *Web*. 15 June 2011. <[http://en.wikipedia.org/wiki/Anti-reflective\\_coating](http://en.wikipedia.org/wiki/Anti-reflective_coating)>

“Eyeglass Lens Coatings: Anti-Reflective, Scratch-Resistant, Anti-Fog and UV” by DeFranco, Liz and Heiting, Gary *All About Vision* © 2000-2011 Access Media Group LLC. December 2010 *Web*. 28 June 2011. <http://www.allaboutvision.com/lenses/coatings.htm#ixzz1QbNR7uFp>

“Diffraction” by David Darling *Copyright © The Worlds of David Darling • Encyclopedia of Alternative Energy* n.d. *Web*. 12 June 2013. <http://www.daviddarling.info/encyclopedia/D/diffraction.html>

*Georgia Tech Nanotechnology Research Center: Equipment* ©2011 Georgia Institute of Technology n.d. *Web*. 20 June 2011. <http://grover.mirc.gatech.edu/equipment/textInstructions.php?id=88>

“How CDs Work” by Marshall Brain *How Stuff Works Express: A Discovery Company*. © 1998-2011 HowStuffWorks, Inc. 30 October 2008. *Web*. 14 July 2011. <http://express.howstuffworks.com/express-cd.htm>

“How do Holograms Work” by Tracy V. Wilson *How Stuff Works: A Discovery Company*. © 1998-2011 HowStuffWorks, Inc. n.d. *Web*. 14 July 2011. <http://science.howstuffworks.com/hologram.htm>

# REFERENCES

- “How do Lasers Work” by Matthew Weschler *How Stuff Works: A Discovery Company*. © 1998-2011 HowStuffWorks, Inc. n.d. Web. 14 July 2011. <http://science.howstuffworks.com/laser1.htm>
- “How do Photovoltaics Work” by Gil Knier *NASA SCIENCE: Science News* NASA 6 April 2011 Web. 5 July 2011. <http://science.nasa.gov/science-news/science-at-nasa/2002/solarcells/>
- “How a Spectrometer Works” by David Scott *eHow*© 1999-2013 Demand Media, Inc. Web. 11 June 2013. [http://www.ehow.com/how-does\\_5381532\\_spectrometer-works.html#ixzz2Vvv5FJlm](http://www.ehow.com/how-does_5381532_spectrometer-works.html#ixzz2Vvv5FJlm)
- “[Introduction to Physics. Final Study Guide](https://wikis.engrade.com/physicsintro/physicsintro27) › Light” *engrade*. n.d. Web. 12 June 2013. <https://wikis.engrade.com/physicsintro/physicsintro27>
- “Iridescent Colors Caused by Interference: Iridescence”. *Causes of Color* n.d. Web. 29 June 2011. <http://www.webexhibits.org/causesofcolor/15.html>
- “Optical Coating” *Wikipedia* Wikimedia Foundation, Inc. 13 June 2010 Web. 15 June 2011. <[http://en.wikipedia.org/wiki/Optical\\_coating](http://en.wikipedia.org/wiki/Optical_coating) >
- “Pioneers in Optics: Friedrich Johann Karl Becke”. *Molecular Expressions: Science, Optics and You* © 1998-2010 Michael E. Davidson and the Florida State University. 18 November 2006 Web. 29 June 2011. <http://micro.magnet.fsu.edu/optics/timeline/people/becke.html>
- “Theory and Fabrication of Integrated Circuits: GT7 – SiO<sub>2</sub> Color Chart” *ECE Illinois* Copyright © 2007, 2008, 2009, 2010, 2011 The Board of Trustees at the University of Illinois. n.d. Web. 28 June 2011. <http://fabweb.ece.uiuc.edu/gt/gt/gt7.aspx>
- “Thin-Film Battery Attains Commercial Availability” *ThinFilmsBlog* 13 December 2007 Web. 28 June 2011. <<http://www.thinfilmsblog.com/2007/12/thin-film-battery-attains-commercial.html>>

# REFERENCES

- “Thin Film Battery Overview” *Copyright © 2011 Oak Ridge Micro-Energy*, 3 January 2011 Web. 15 June 2011 <<http://www.oakridgemicro.com/tech/tfb.htm#up>>
- “What Is a Spectrometer?” by Dyna Whiting *eHow*. © 1999-2013 Demand Media, Inc. Web. 11 June 2013. <[http://www.ehow.com/about\\_5372347\\_spectrometer.html#ixzz2VvsNbxju](http://www.ehow.com/about_5372347_spectrometer.html#ixzz2VvsNbxju)>

# TEACHER INSTRUCTIONS FOR DIFFRACTION LAB

## MATERIALS

CDs, DVDs, diffraction gratings of various sizes, laser pointers, screen/poster board, tape, rulers/meter-sticks, clamps, AFM images of a CD and DVD gratings (provided), *razor blades*, *tweezers*, *packing tape*(for making the diffraction gratings from the CDs/DVDs)

## ADVANCED PREPERATIONS

### RETRIEVAL OF PHYSICAL DIFFRACTION GRATINGS FROM CDs AND DVDs

#### DVDs

- 1) Identify the two layers and take a razor blade and carefully slice between them. They should separate fairly easily.
- 2) Discard the protective polycarbonate coating.
- 3) Take large pieces of tape (packing tape works well) and gently press the tape onto the reflective surface and then rip the tape off. Continue this until the majority of the metal coating is removed. (Sometimes small pieces of metal are difficult to remove – this is not a problem just use a portion that is clear for the large scale experiment or for imaging purposes).
- 4) Cut into 3 cm x 3 cm sections (large enough that they can be clamped and used with a laser pointer)



Clockwise from top left

- 1) Split along the edge
- 2) Separate into 2 layers
- 3) Peel off the reflecting layer with tape
- 4) You now have a transmission grating

#### CDs

- 1) An unpainted CD is required (CD-R's and CD-RW's work well)
- 2) Take large pieces of tape (packing tape works well) and gently press the tape onto the top surface (the side that can be written on) and then rip the tape off. Continue this until the majority of the metal coating is removed. (There are two layers of metal – the top layer is the one that can be written on, the lower layer is the reflective layer – both must be removed).



Scratch the label surface



Peel off the label and the reflecting layer



Transmission grating

## SAFETY INFORMATION

### LASERS

Most lasers used in high school laboratories are the continuous wave, low power (0.5 - 3.0 mW.) lasers. The main danger is possible damage to the retina if a student looks directly into the beam or non-diffused reflection. Remind the students of this and direct them to be very careful when using the lasers.

### RAZOR BLADES

The blades are quite sharp and could cut or puncture a student. The teacher may want to handle the process of opening the DVDs prior to the student's lab.

## DIRECTIONS FOR THE ACTIVITY

- 1) Discuss interference, diffraction and diffraction gratings.
- 2) Demonstrate diffraction with different types of gratings.
- 3) Divide the class into two – four student groups.
- 4) Review the general procedures of the lab and remind the students about the safety concerns when using lasers.
- 5) After the data is collected from the CD and DVD gratings discuss the size of these gratings and how small a distance the grooves are from one another. Ask the students if they are able to measure the grooves with a ruler or able to see the grooves under an optical microscope (if an optical microscope is available demonstrate this for the class).
- 6) Explain to the students that objects on the micro- and nano-scale must have special equipment to be viewed. Discuss the basic concept of the AFM (make sure the students understand that the images that they see are not photographs but digital interpretations of the topography of the object).
- 7) Depending on time and equipment restraints there are three options for the second part of the lab:

Use the hard copies of the images provided and with a ruler measure the distance between tracks. Have the students perform the calculations to determine the distance between tracks and compare to the other data obtained.

**Step 1: Prepare CDs and DVD s to use as diffraction grating (see above)**

**Step 2: Gather materials and set up each group for the lab**

**Step 3: Explanation of Diffraction Grating Set up**

Obtain a laser and fix it to a stand such that the laser is held horizontally and securely using a clamp. If you do not have enough ring stands then one student can hold the laser in place.

Use another stand to position the diffraction grating in front of the laser such that the light from the laser is incident normally on the grating. Place the grating as close to the laser as possible.

Use a blank wall/white board/poster board as the screen so that the diffraction pattern can be observed clearly. It is preferable that the room be dark so that it is easy to observe the diffraction pattern. The laser should be positioned about a meter (or less) away from the screen.

Switch on the laser and look for the central non-diffracted beam spot on the screen. The first order maxima should be visible on either side of the central spot. The second and third order can also be observed but may not be as bright as the first order image. A student from each group should mark these spots.

#### Step 4: Diffraction pattern using the CD/DVD

Use same procedure as diffraction gratings, however:

If the images are not on a horizontal on the screen rotate the CD and change its orientation until you get the images on a horizontal line. Note that the tracks are spiral in a CD or DVD and so the spacings are not exactly parallel. The treatment for a plane transmission grating can be applied to a CD or DVD grating to a good approximation. This is also why the first and second order images may not be exact spot images of the laser beam.

#### Picture and Diagram of the experimental set up



#### DIFFRACTION EQUATIONS

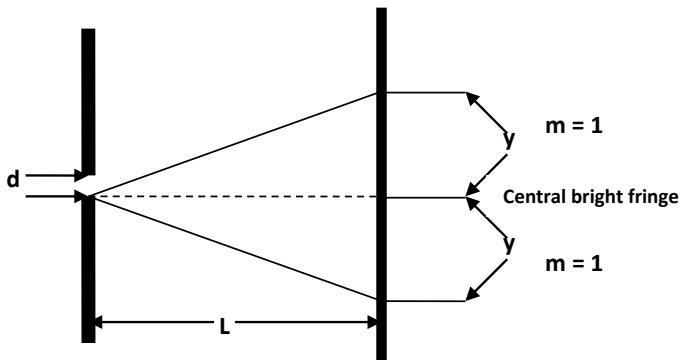
$$d \sin \theta_{\text{calc.}} = m \lambda \quad \text{and} \quad y = L \tan \theta_{\text{obser.}}$$

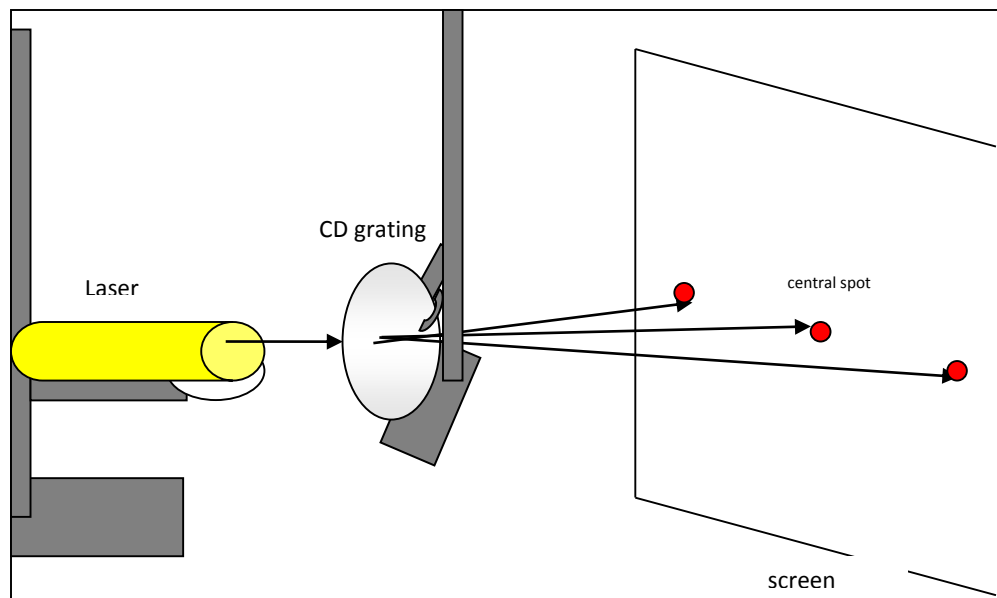
$d$  = distance between slits

$\theta$  = path angle

$m$  = order number

$\lambda$  = wavelength of light





## Step 5: Measurement and Analysis

### Diffraction Gratings:

- 1) After the set-up and the fringes are marked:
  - a) Measure the distance of the first order maxima from the central spot on either side and calculate its average ( $y$ ). Either side should give a very close value.
  - b) Measure the distance of the laser to the screen ( $L$ ).
  - c) Use the label on the laser to identify the wavelength of the laser beam that is used ( $\lambda$ ).
  - d) Convert the diffraction grating size to distance between slits in meters. Ex) 100 lines/mm  $\rightarrow 1/100 = 0.01 \text{ mm/line} \rightarrow 1 \text{ E } -5 \text{ m/line}$
  - e) Remind students to have their calculators set in degrees and not radians.

Since the angle of diffraction for the first order is not really small (about  $22^\circ$ ), the approximation that  $\sin \theta = \tan \theta$  is not valid. Evaluate  $\tan \theta$  using the equation given in Step 4; if the first order image is too spread out on the screen on either side try reducing the distance of the screen to the laser setup.

$x$  = distance from maximum on screen

$d$  = distance from grating to screen

$\lambda_{\text{laser}}$  = wavelength of laser

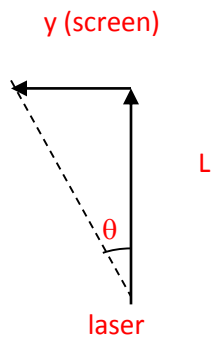
$\theta_{\text{diffraction}}$  = calculated angle of diffraction

$d$  = grating separation (average track spacing)

To find  $\theta_{\text{calc}}$  use the values for  $d$ ,  $\lambda$ , and  $m = 1$  with equation 1.

**Equation 1:**  $d (\sin \theta_{\text{calc}}) = m\lambda$   $m = 0, \pm 1, \pm 2, \dots \rightarrow \theta_{\text{calc}} = \sin^{-1}(m\lambda/d)$

To find  $\theta_{\text{observ}}$  measure distance from grating to screen (L) and the first order distance from central bright fringe (y) and then by using equation 2 calculate the angle (observed).

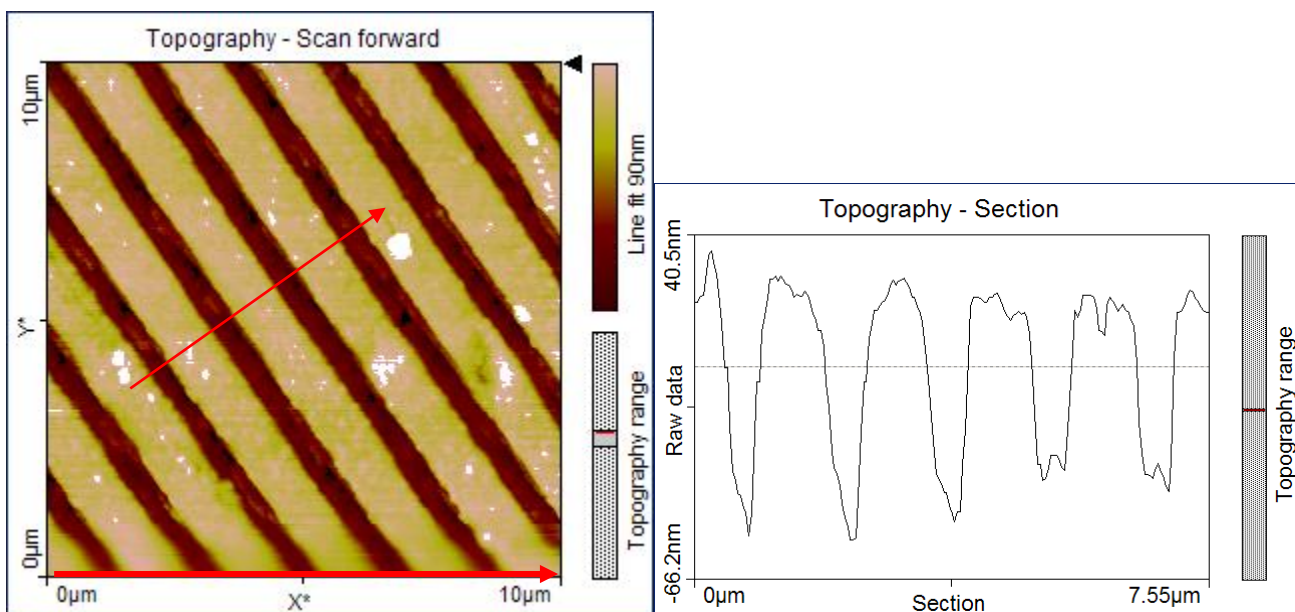


**Equation 2:**  $y = L \tan \theta_{\text{observ}} \rightarrow \theta_{\text{observ}} = \tan^{-1}(y/L)$

**Calculate Percent Error:** Have the students compare the observed and calculated angles by using percent error. I have gotten pretty good results with this. The main error is that the students did not convert d correctly.  $|O - A|/A \times 100\%$  (O is the observed angle value and A is the calculated value)

#### Step 6: Track Pitch of the CD/DVD

Repeat the same procedure for a CD/DVD. With the DVD, it may be difficult to observe the second and the third order images; it is also advisable to move the laser arrangement much closer to the screen so that the first order image is closer to the central non-diffracted spot. Measure y and L using the same procedure in Step 5. Using equation 2 calculate the angle and then use that angle and the wavelength of the laser and  $m = 1$  to calculate d. Then measure spacing between tracks on the given AFM images (remind the students to convert values from their ruler to the nano-scale), this will be  $d_{\text{measured}}$ . Have the students calculate percent error with O as the measured d and A as the calculated d.



**Fig1a. AFM image : Sample : Memorex CD 750 MB;**  
blank; scan size 10 micrometer

**1b. Line scan of the image**

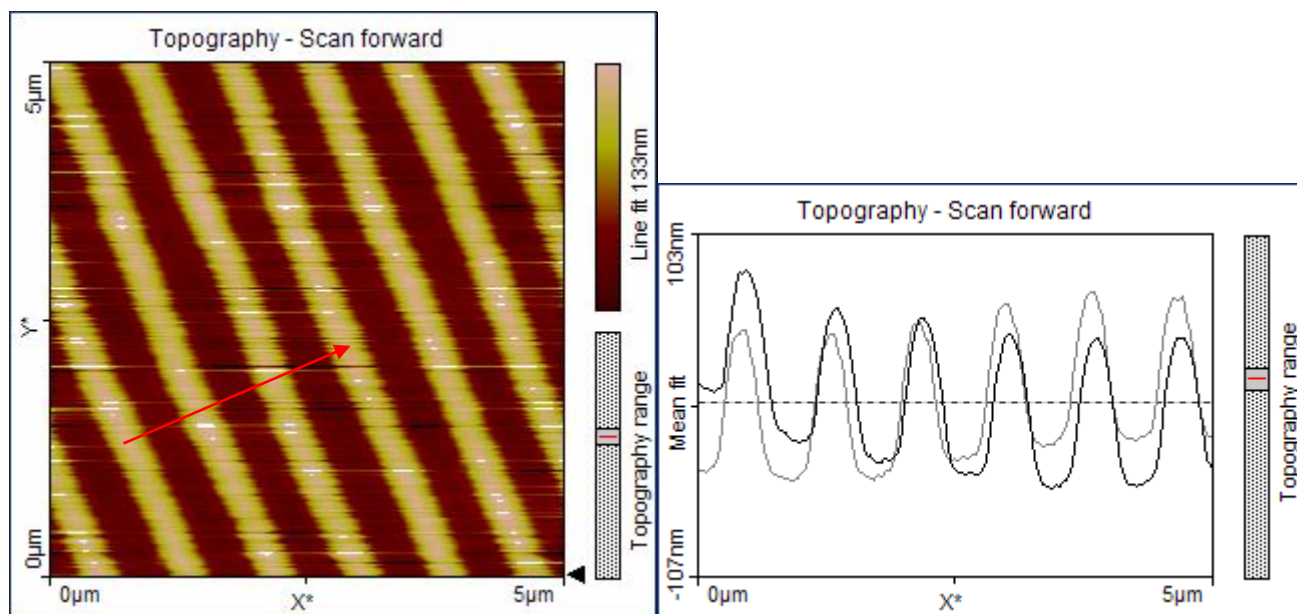
Calculations for the CD image:

Scale factor: 7.2 cm = 10 micrometers; 1 cm = 1.39 micrometers

4 x track pitch = 4.4 cm = 6.12 micrometers

track pitch = 1.53 micrometers

(Note that the grating element is the combined width of the opaque and transparent lines in a regular grating;  
so measure the distance between tracks as including the width of the track – See arrow in scan)



2a. AFM image Sample : Sony DVD-R 4.7 GB;  
Blank, scan size 5.0 micrometer

Fig 2b- Line scan of the sample

Calculations for the DVD image :

Scale factor: 7.2 cm = 5 micrometers; 1 cm = 0.694 micrometer

3x track pitch = 3.4 cm = 2.36 micrometers

track pitch = 1.13 cm = 0.787 micrometer

# DIFFRACTION GRATING LAB

## TEACHER'S COPY

### MATERIALS:

Diffraction gratings, a CD/DVD with aluminum coating removed, laser pointer, ring-stand with clamp, and white screen (or poster board)

### PROCEDURE:

Use the information on the diffraction gratings to compare the calculated angle of diffraction with the measured one (first order maximum). Use a CD/DVD as a diffraction grating and determine the distance between the grooves.

### DATA:

Wavelength of laser ( $\lambda$ ): \_\_\_\_\_ m

#### DIFFRACTION EQUATIONS

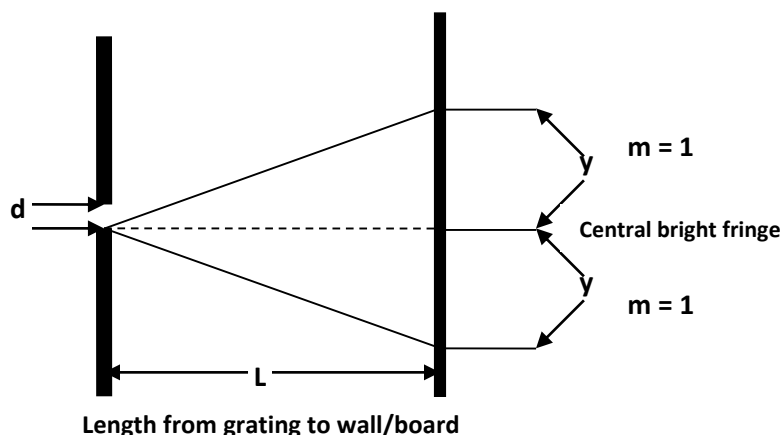
$$d \sin \theta_{\text{calc.}} = m \lambda \quad \text{and} \quad y = L \tan \theta_{\text{observed}}$$

$d$  = distance between slits

$y$  = distance from central to 1<sup>st</sup> bright fringe

$\theta$  = path angle

$m$  = order number



Grating	$d$ (meters)	$y$ (meters)	$L$ (meters)	$\theta_{\text{calculated}}$	$\theta_{\text{observed}}$	% Error
100 lines/mm	1 E -5					
300 lines/mm	3.33 E -6					
530 lines/mm	1.89 E -6					
600 lines/mm	1.67 E -6					

--	--	--	--	--	--	--

### For the CD/DVD:

Calculate the  $\theta_{\text{diffraction}}$  for the first order maximum using the measured  $y$  and  $L$ . Then using the calculated angle solve for  $d$  using  $d\sin\theta_{\text{calc.}} = m\lambda$ . Compare it to the  $d$  measured from the AFM image of the CD/DVD using the % Error equation.

y (meters)	L (meters)	$\theta_{\text{diffraction}}$	$d_{\text{calculated}}$ (meters)	$d_{\text{measured}}$ (meters)	% Error

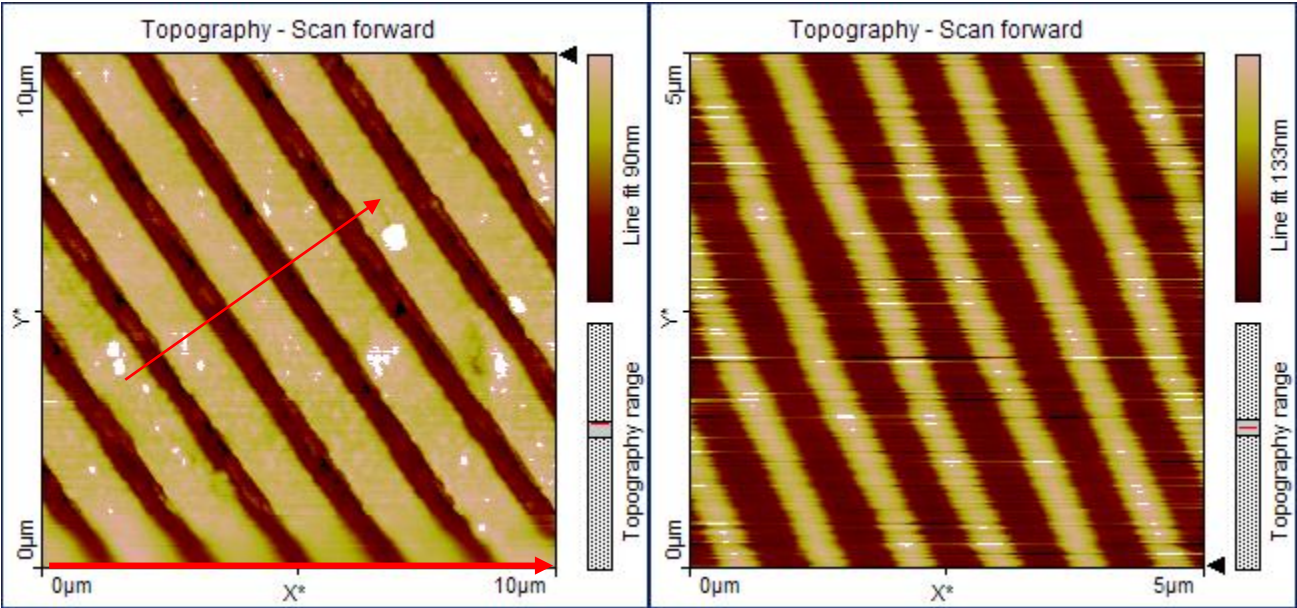
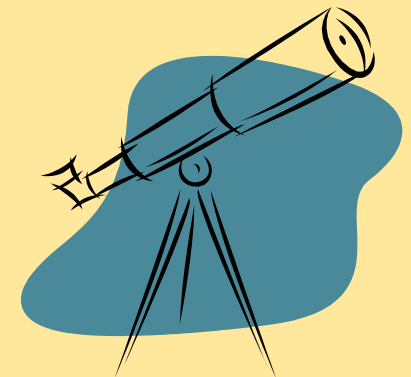
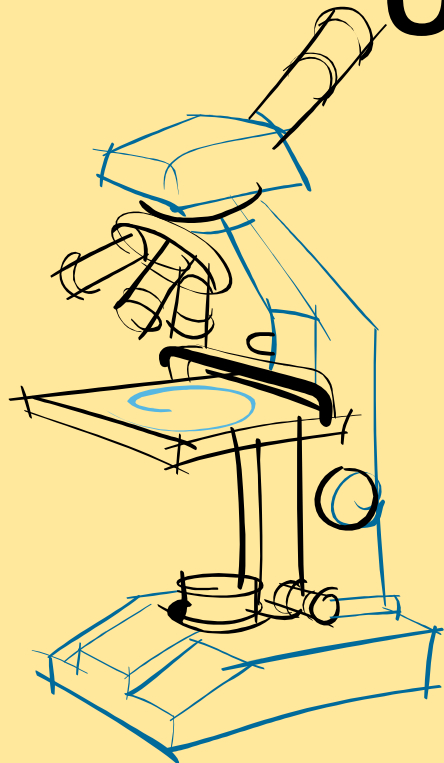


Fig1a. AFM image : Sample : Memorex CD 750 MB; blank; scan size 10 micrometer

2a. AFM image Sample : Sony DVD-R 4.7 GB; Blank, scan size 5.0 micrometer



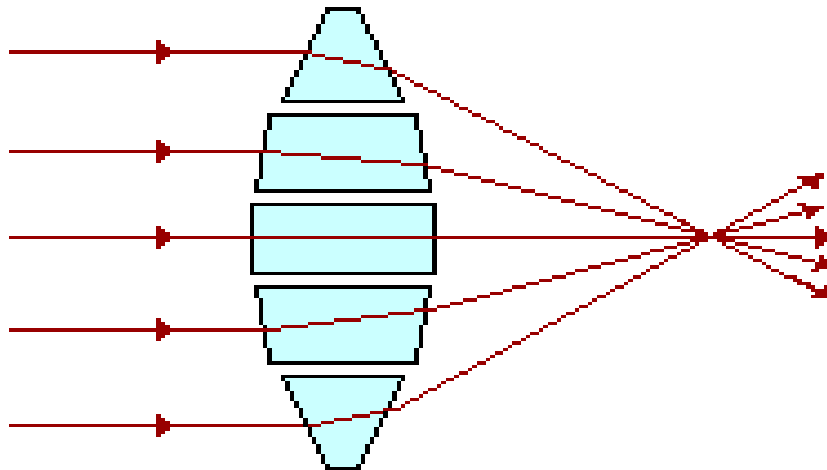
# REFRACTION, DIFFRACTION AND OPTICAL INSTRUMENTS



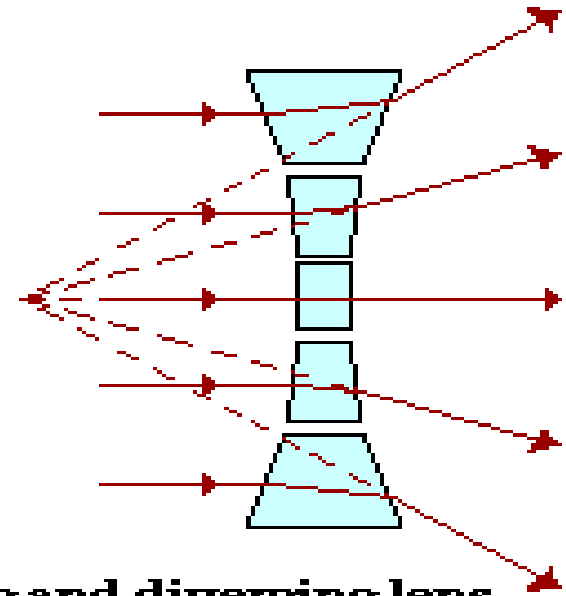
# LENSES

- Converging lens are thicker at the middle and bend the ray of light inward.
- Diverging lens are thicker at the edge and bend the ray of light outward.
- The images formed can be either real or virtual, depending on the type of lens and on the placement of the object.

## Converging Prisms

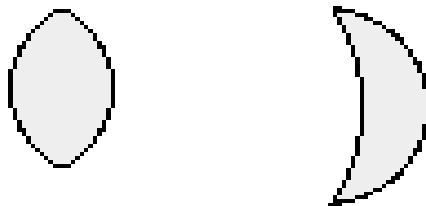


## Diverging Prisms



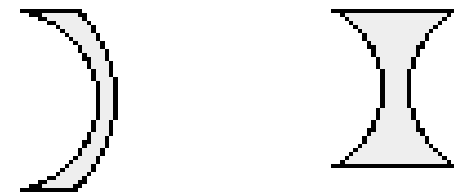
**A set of prisms acting as a converging and diverging lens.**

## Converging Lenses



**thicker across the middle  
thinner at its edges  
serves to converge light**

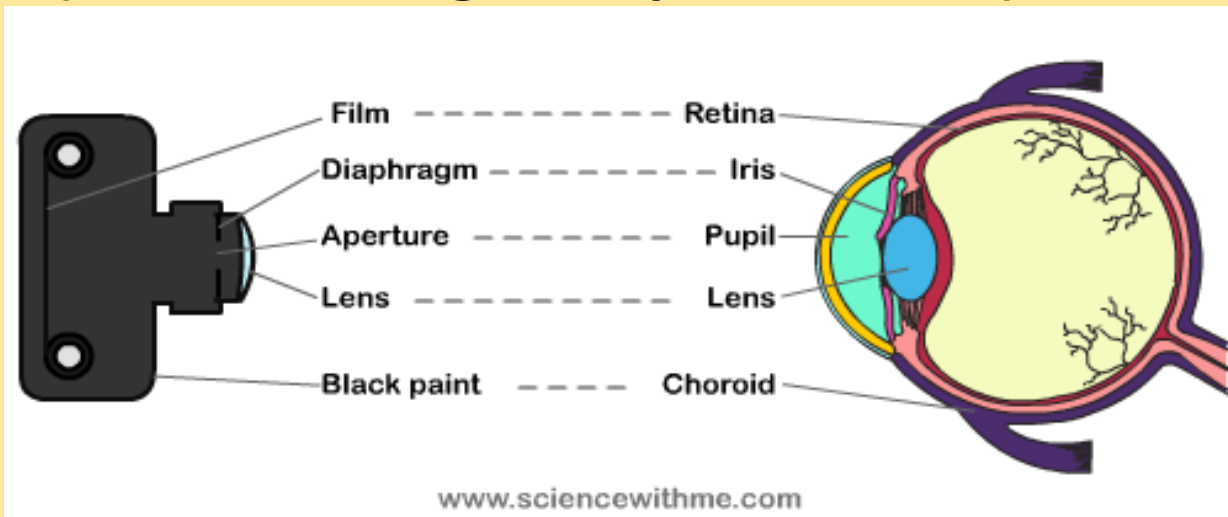
## Diverging Lenses



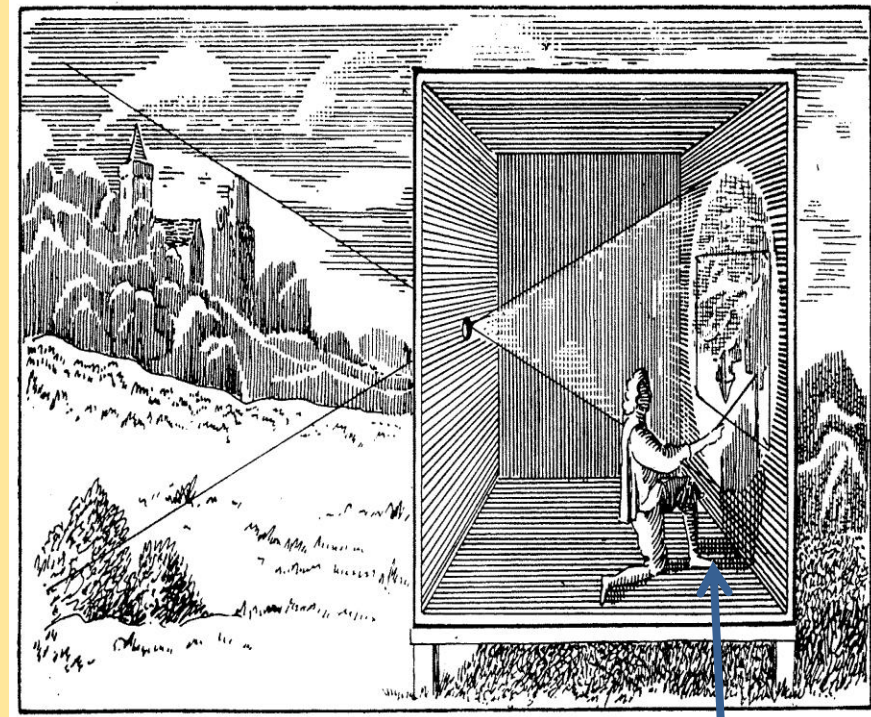
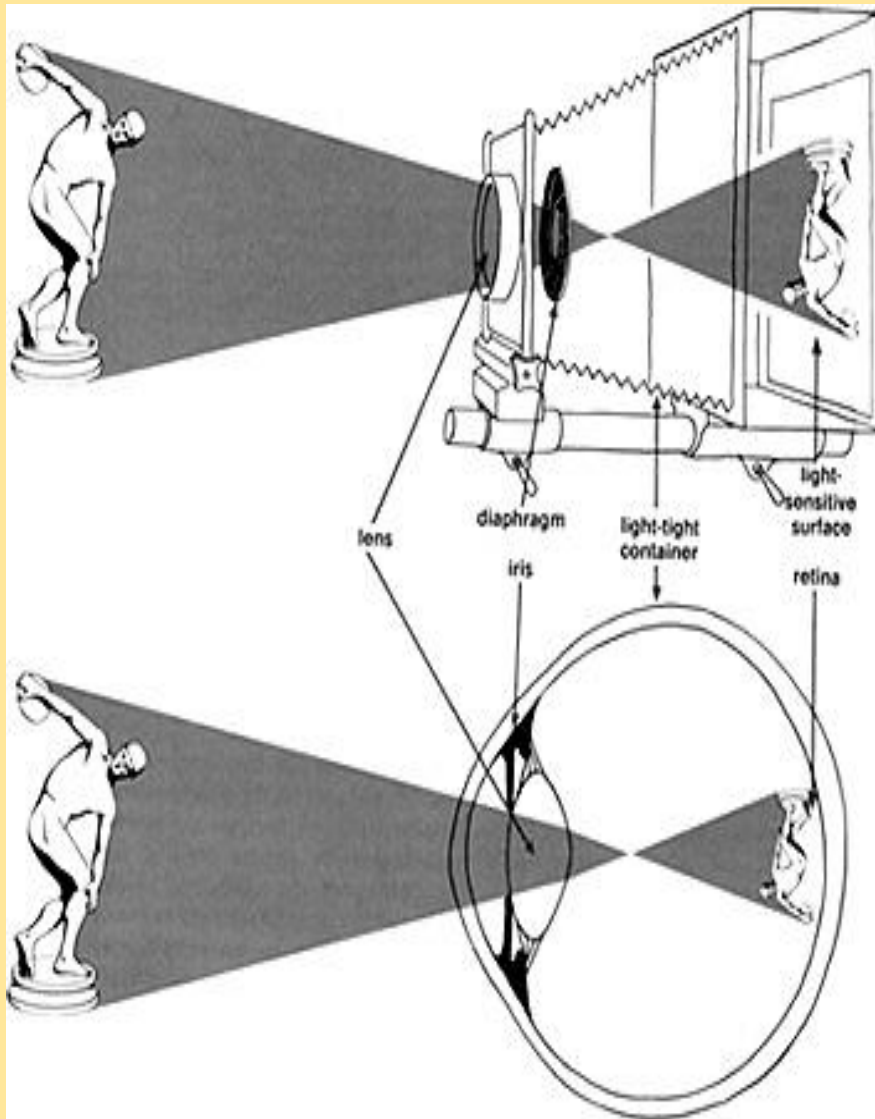
**thinner across the middle  
thicker at its edges  
serves to diverge light**

# THE CAMERA AND THE EYE

- The human eye and a camera are structured and work very similarly to each other.
- They both have a light opening (iris or aperture) lens assembly and an imaging sensor.
- The lens assembly takes in a portion of the light reflected from an object, and focuses it onto a imaging sensor. The imaging sensor then changes the light into a signal, either electronic (film or charge coupled device) or neural (retina).



# THE CAMERA AND THE EYE



<http://www.teamlocals.co.uk/portsmouth-natural-history-museum-transformed-into-camera-obscura-for-family-workshop-044>

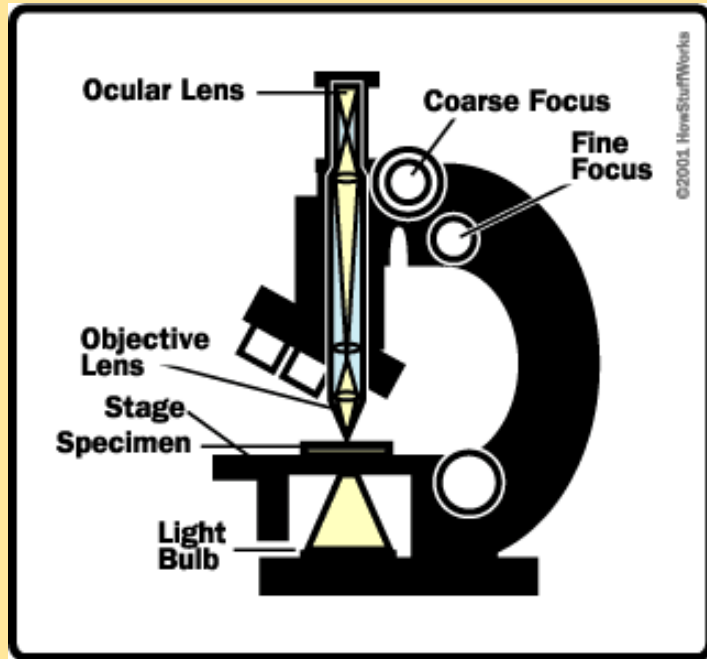


What are [these](#)?

# COMBINATION OF THIN LENSES

- If 2 lenses are used to form an image the image of the 1<sup>st</sup> lens is calculated as though the 2<sup>nd</sup> lens were not present.
- The image formed by the first lens is treated as the object for the second lens.
- The overall magnification of a system of lenses is the product of the magnifications of the separate lenses.

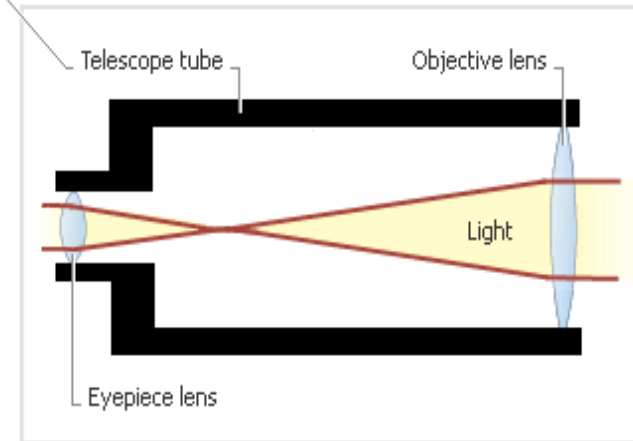
# LIGHT MICROSCOPE AND REFRACTING TELESCOPE



<http://science.howstuffworks.com/light-microscope5.htm>



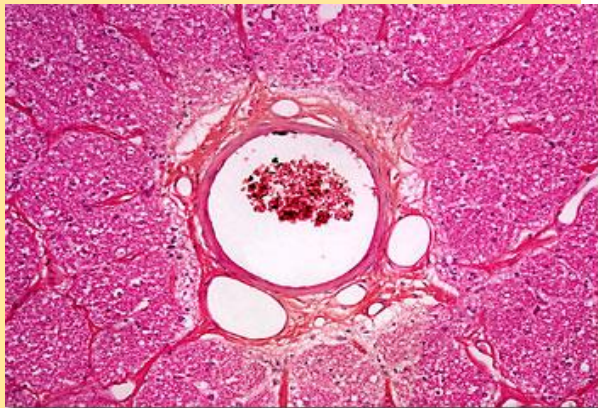
Refracting Telescope



Refracting telescopes have two main problems—images are not always clear because the light is being bent and the size of the lens is limited (which limits the power of the telescope). Reflecting telescopes use mirrors instead of lenses and are the type used in very large telescopes.

An Optic Nerve Cell:

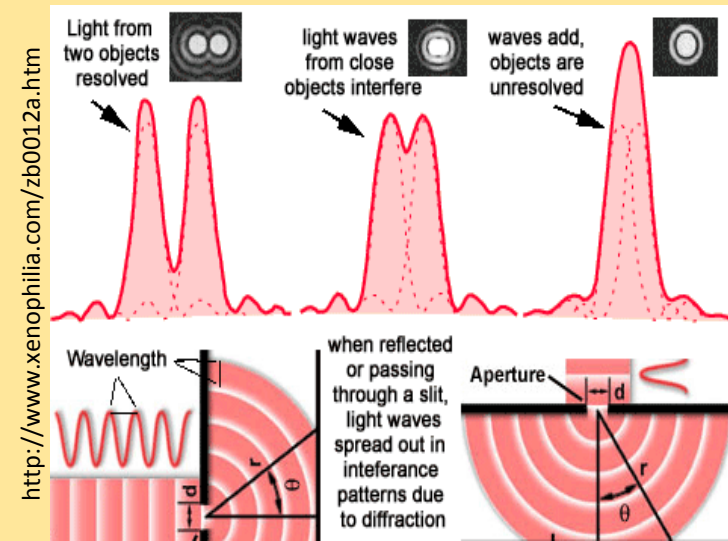
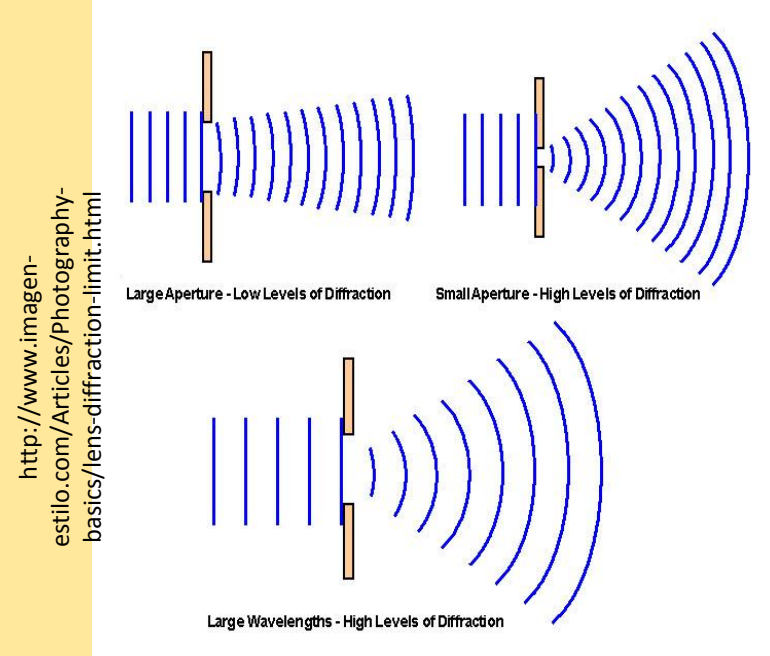
[http://micro.magnet.fsu.edu/p\\_rimer/anatomy/brightfieldgaller/opticnerve20xsmall.html](http://micro.magnet.fsu.edu/p_rimer/anatomy/brightfieldgaller/opticnerve20xsmall.html)



[http://www.odec.ca/projects/2005/dong5a0/public\\_html/RFracTeles.png](http://www.odec.ca/projects/2005/dong5a0/public_html/RFracTeles.png)

# DIFFRACTION AND RESOLUTION

- Resolution: ability of an optical instrument to resolve detail in the object that is being imaged. It depends on wavelength and aperture width.
- The resolution of an optical instrument can be limited by factors such as flaws in the lenses or misalignment. However, there is a max to the resolution of any optical instrument due to diffraction.



# RESOLVING POWER

- Resolving power is the ability of an optical instrument to separate two images that are close together. It is greater for short wavelengths.

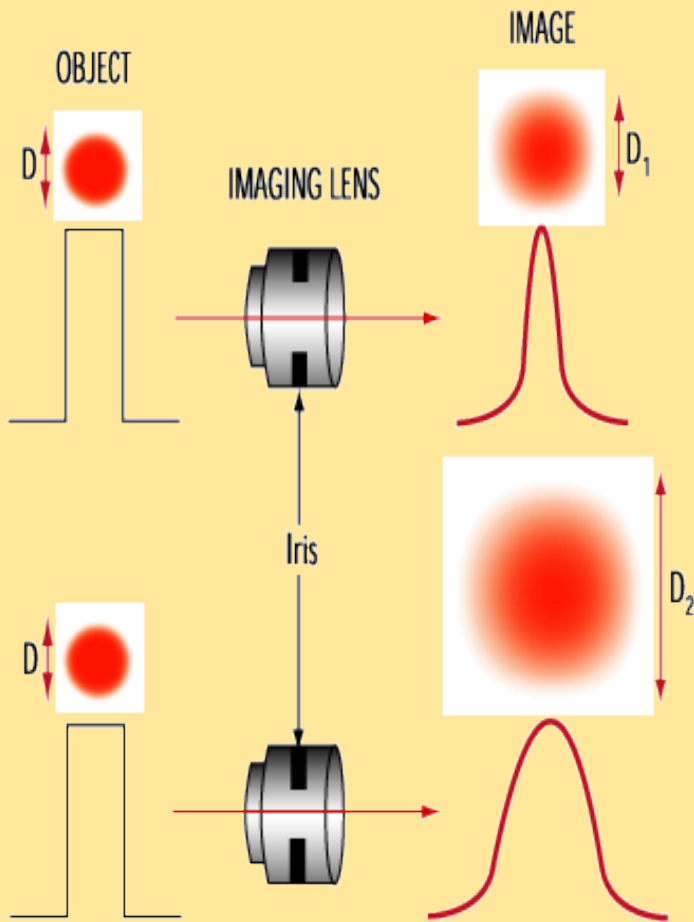
$$\sin \theta = 1.22 \frac{\lambda}{D}$$

$\theta$  = Angular Resolution

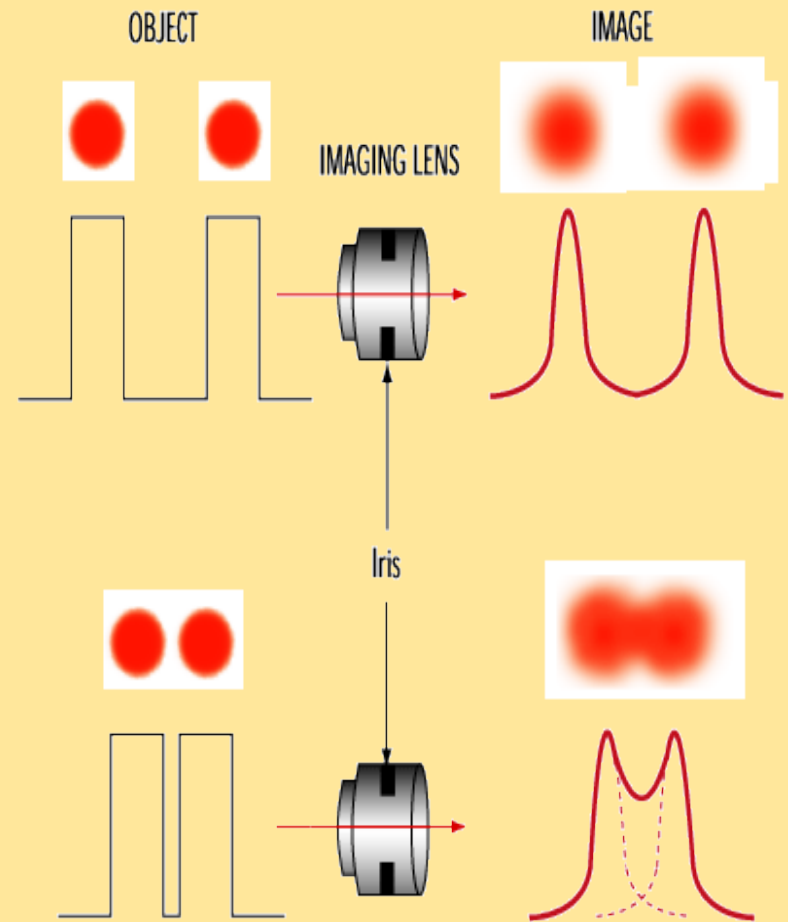
$\lambda$  = wavelength of light

$D$  = diameter of the lens' aperture

# DIFFRACTION AND OPTICAL INSTRUMENTS



***Diffraction increases as the imaging lens iris is closed***

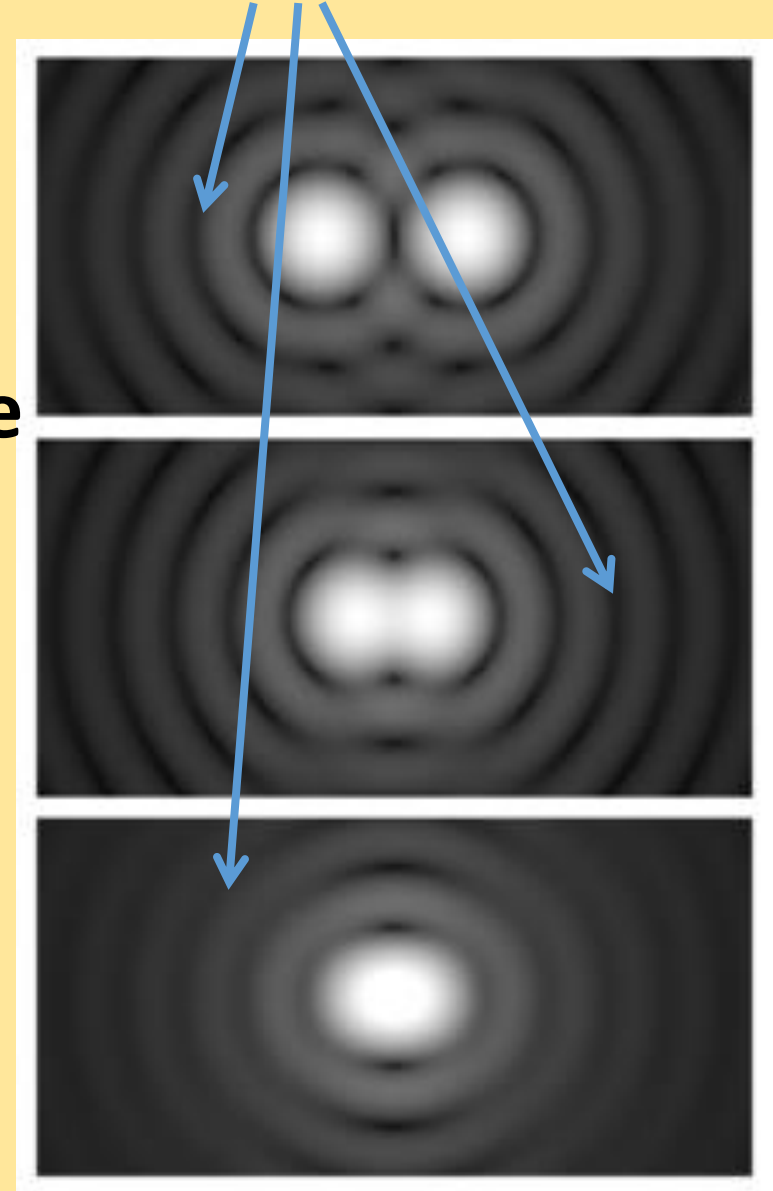


***Resolution/contrast decrease as the diffracted dots approach each other because they begin to blend together***

# RESOLUTION

Airy diffraction patterns generated by light from two points passing through a circular aperture, such as the pupil of the eye. Points far apart (top) or meeting the Rayleigh criterion (middle) can be distinguished. Points closer than the Rayleigh criterion (bottom) are difficult to distinguish.

Airy diffraction patterns



# INCREASING RESOLUTION IN OPTICAL MICROSCOPES

## TIPS TO GET A BETTER RESOLUTION

- 1) Clean coverslips and specimen slides
- 2) Use correct coverslips (thickness)
- 3) Use the correct immersion oil/fluid
- 4) Use a Super resolution Microscope

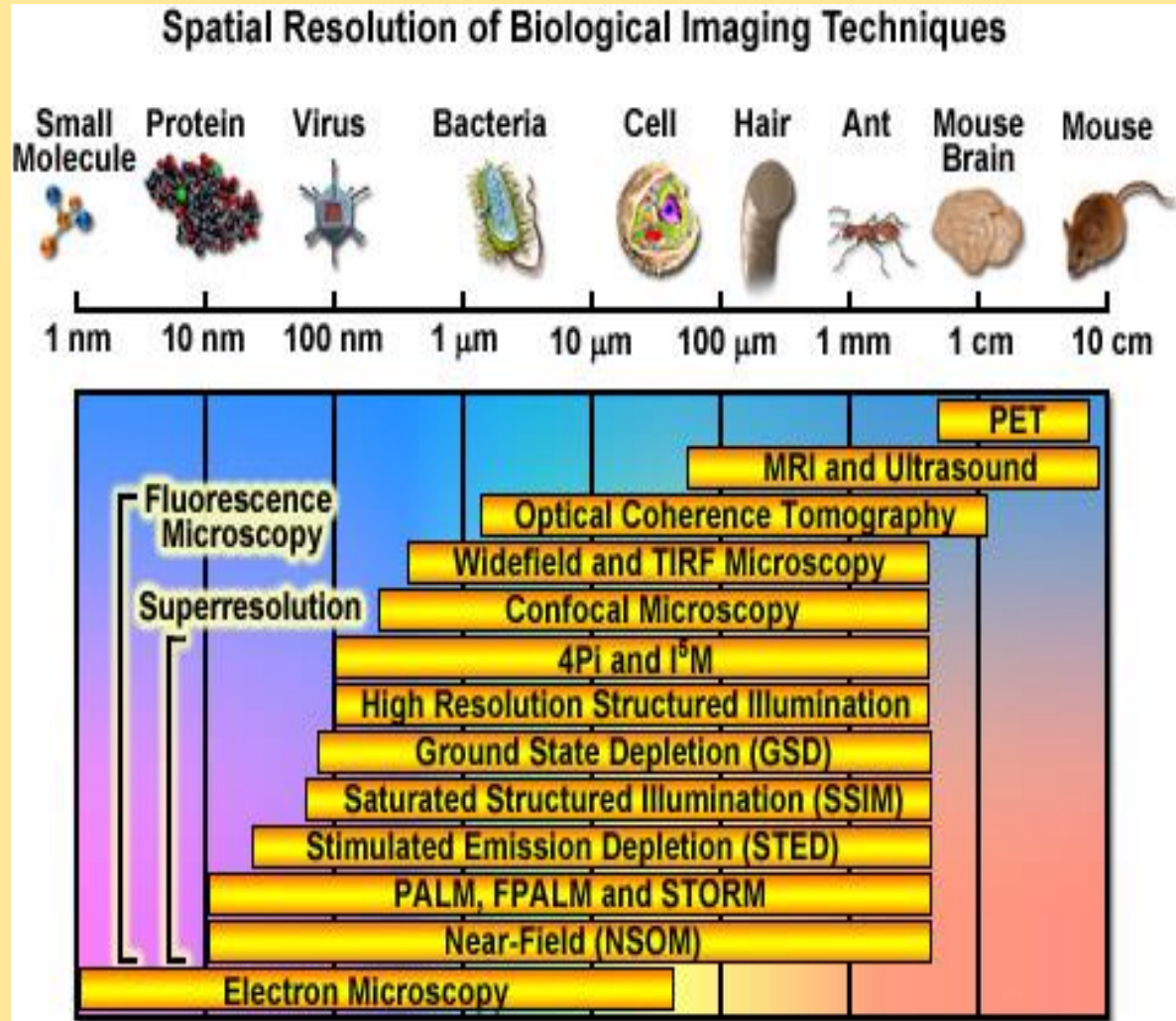
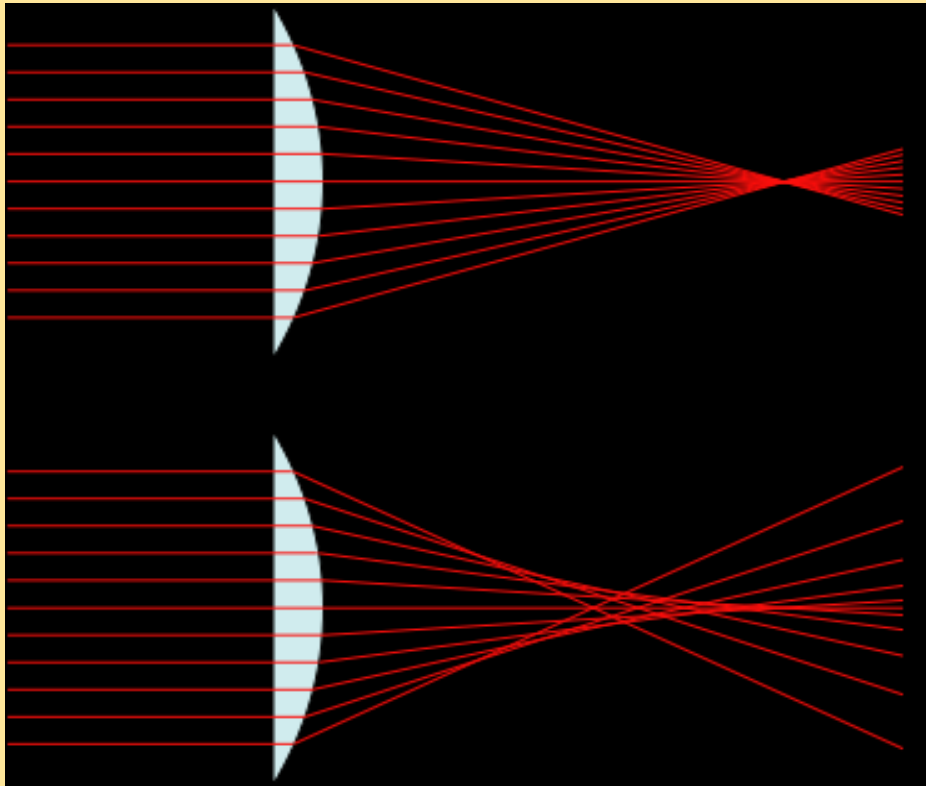


Figure 1

# LENS ABERRATIONS

- As with spherical mirrors, spherical aberration occurs for lenses also.
- Spherical aberration creates a blurry image due to the light rays not converging/diverging in the same place.
- Chromatic aberration is the focusing of different colors of light at different distances behind a lens.

# SPHERICAL ABERRATIONS



[http://commons.wikimedia.org/wiki/File:Spherical\\_aberration\\_2.svg](http://commons.wikimedia.org/wiki/File:Spherical_aberration_2.svg)

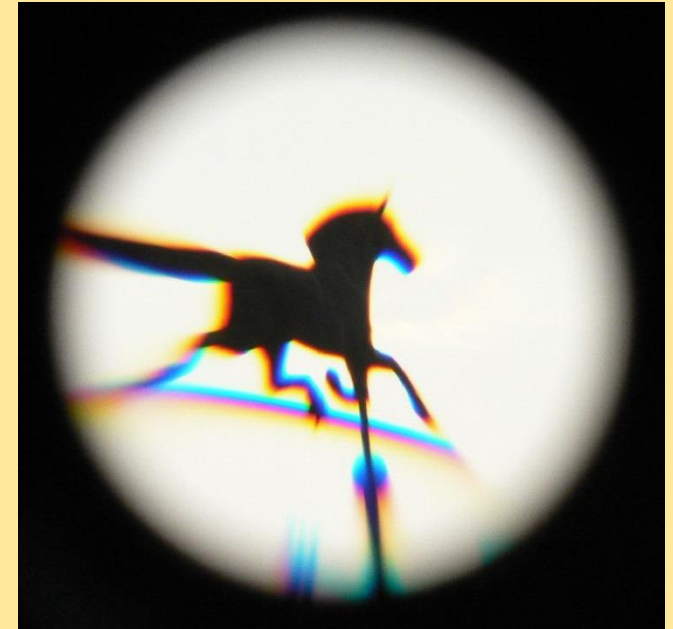


<http://www.dofpro.com/sagallery.htm>

# CHROMATIC ABERRATIONS

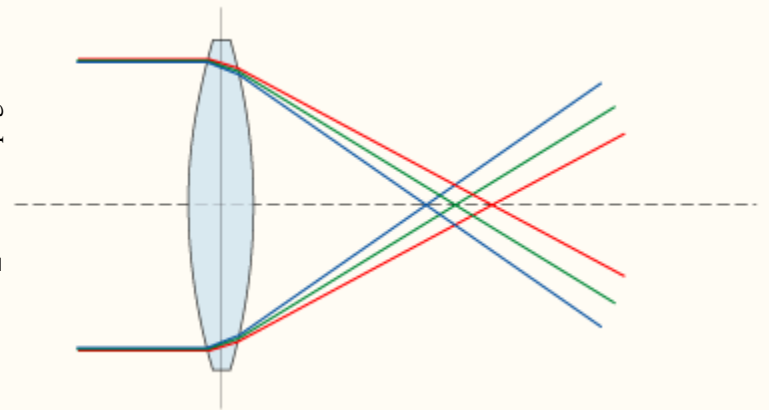


[http://commons.wikimedia.org/wiki/File:Chromatic\\_aberration\\_%28comparison%29\\_-\\_enlargement.jpg](http://commons.wikimedia.org/wiki/File:Chromatic_aberration_%28comparison%29_-_enlargement.jpg)



<http://www.tlc-systems.com/artzen2-0047.htm>

[http://commons.wikimedia.org/wiki/File:Chromatic\\_aberration.png](http://commons.wikimedia.org/wiki/File:Chromatic_aberration.png)



# REFERENCES

- Serway, Raymond A., and Jerry S. Faughn. Holt Physics. Austin, Texas: Holt, Rinehart and Winston, 2000.
- Smith, Steven W. Ph.D. The Scientist and Engineer's Guide to Digital Signal Processing © 1997-2011 by California Technical Publishing. Web. 06 June 2014. <http://www.dspguide.com/copyrite.htm>
- “Introduction to Superresolution Microscopy”. Education in Microscopy and Digital Imaging. Carl Zeiss and Molecular Expressions. Web. 06 June 2014 <http://zeiss-campus.magnet.fsu.edu/articles/superresolution/introduction.html>
- “Refraction and Ray Model of Light”. The Physics Classroom. © 1996-2010 The Physics Classroom, All rights reserved. comPADRE. June 18, 2010. [<http://www.physicsclassroom.com/Class/refrn/>]
- “Refracting and Reflecting Telescopes”. ORACLE Think Quest Education Foundation. 2001. ORACLE Think Quest Education Foundation. June 21, 2010. [[http://library.thinkquest.org/J0112188/refracting\\_and\\_reflecting\\_telescopes.htm](http://library.thinkquest.org/J0112188/refracting_and_reflecting_telescopes.htm)]

# GPS: PHYSICS

## **SP4. Students will analyze the properties and applications of waves.**

- a. Explain the processes that results in the production and energy transfer of electromagnetic waves.
- b. Experimentally determine the behavior of waves in various media in terms of reflection, refraction, and diffraction of waves.
- c. Explain the relationship between the phenomena of interference and the principle of superposition.
- e. Determine the location and nature of images formed by the reflection or refraction of light.

## **SP1. Students will analyze the relationships between force, mass, gravity, and the motion of objects.**

- d. Measure and calculate the magnitude of frictional forces and Newton's three Laws of Motion.
- e. Measure and calculate the magnitude of gravitational forces.

## **SP3. Students will evaluate the forms and transformations of energy.**

- a. Analyze, evaluate, and apply the principle of conservation of energy and measure the components of work-energy theorem by
  - • describing total energy in a closed system.
  - • identifying different types of potential energy.
  - • calculating kinetic energy given mass and velocity.
  - • relating transformations between potential and kinetic energy.
- b. Explain the relationship between matter and energy.
- e. Demonstrate the factors required to produce a change in momentum.

# NATIONAL SCIENCE STANDARDS

- **MOTIONS AND FORCES**

- Objects change their motion only when a net force is applied. Laws of motion are used to calculate precisely the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated using the relationship  $F = ma$ , which is independent of the nature of the force. Whenever one object exerts force on another, a force equal in magnitude and opposite in direction is exerted on the first object.
- Gravitation is a universal force that each mass exerts on any other mass. The strength of the gravitational attractive force between two masses is proportional to the masses and inversely proportional to the square of the distance between them.

- **CONSERVATION OF ENERGY AND THE INCREASE IN DISORDER**

- All energy can be considered to be either kinetic energy, which is the energy of motion; potential energy, which depends on relative position; or energy contained by a field, such as electromagnetic waves.

- **INTERACTIONS OF ENERGY AND MATTER**

- Waves, including sound and seismic waves, waves on water, and light waves, have energy and can transfer energy when they interact with matter
- Electromagnetic waves result when a charged object is accelerated or decelerated. Electromagnetic waves include radio waves (the longest wavelength), microwaves, infrared radiation (radiant heat), visible light, ultraviolet radiation, x-rays, and gamma rays. The energy of electromagnetic waves is carried in packets whose magnitude is inversely proportional to the wavelength.
- Each kind of atom or molecule can gain or lose energy only in particular discrete amounts and thus can absorb and emit light only at wavelengths corresponding to these amounts. These wavelengths can be used to identify the substance.

# THIN-FILM INTERFERENCE ACTIVITY

## Objective:

To create a thin-film interference pattern and to explain how this pattern is formed.

## Materials:

- 1) Clear nail polish
- 2) black construction paper
- 3) Aluminum cooking pan (large enough to hold the paper and deep enough for it to be submerged)
- 4) Water

## Procedure:

- 1) Fill the cooking pan with water.
- 2) Place the sheet of construction paper into the pan of water.
- 3) Using the brush of the nail polish, drip in one drop of nail polish onto the center of the water.
- 4) Allow the nail polish time to spread into a thin layer on the surface of the water.
- 5) Lift the construction paper out of the water so that the layer of nail polish coats the paper.
- 6) Set the paper aside to dry.
- 7) Notice the thin-film that appears on the paper.

## Questions:

- 1) What is a thin-film and how thin does it need to be?
- 2) How is the interference pattern created in a thin-film?
- 3) Name two other examples of thin-films that you see out in the world?
- 4) Explain how the index of refraction plays a role in the phase shift of the light rays.
- 5) How is a reddish color produced in the interference pattern? Bluish color?

# THIN-FILM INTERFERENCE ACTIVITY

## TEACHER KEY

### Objective:

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### Materials:

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- 6) Set the paper aside to dry.
- 7) Notice the thin-film that appears on the paper.

### Questions:

- 1) What is a thin-film and how thin does it need to be?

**Constructive and destructive interference of light waves is also the reason why thin films, such as soap bubbles, show colorful patterns. This is known as thin-film interference, because it is the interference of light waves reflecting off the top surface of a film with the waves reflecting from the bottom surface. To obtain a nice colored pattern, the thickness of the film has to be on the order of the wavelength of light.**

- 2) How is the interference pattern created in a thin-film?

**Thin-film interference can take place if these two light waves interfere constructively:**

1. **the light from the air reflecting off the top surface**
2. **the light traveling from the air, through the oil, reflecting off the bottom surface, traveling back through the oil and out into the air again.**

- 3) Name two other examples of thin-films that you see out in the world?

**Soap bubbles, optics coatings, oil on water**

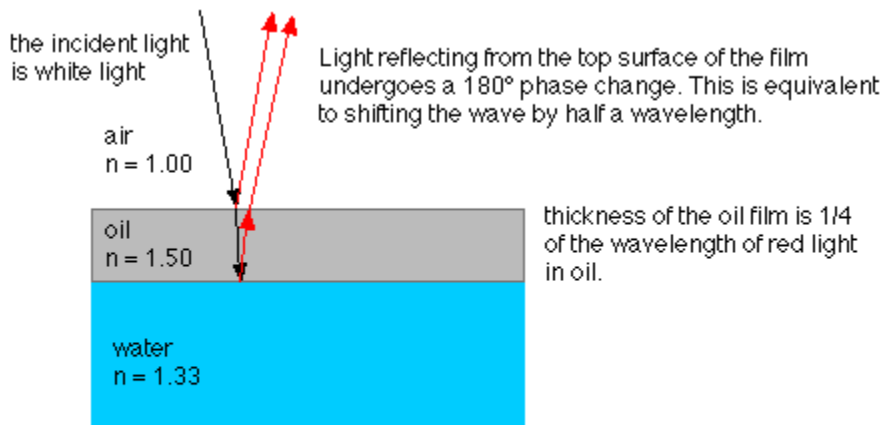
- 4) Explain how the index of refraction plays a role in the phase shift of the light rays.

**An important consideration in determining whether these waves interfere constructively or destructively is the fact that whenever light reflects off a surface of higher index of refraction, a  $180^\circ$  phase shift in the wave is introduced.**

Reflected waves undergo a  $180^\circ$  phase shift when  $n_2 > n_1$ , and no phase shift when reflecting from a medium of lower index of refraction ( $n_2 < n_1$ ).

**Light in air, reflecting off just about anything (glass, water, oil, etc.) will undergo a  $180^\circ$  shift. On the other hand, light in oil, which has a higher  $n$  than water does, will have no phase shift if it reflects off an oil-water interface. Note that a shift by  $180^\circ$  is equivalent to the wave traveling a distance of half a wavelength.**

**To get constructive interference, the two reflected waves have to be shifted by an integer multiple of wavelengths. This must account for any phase shift introduced by a reflection off a higher- $n$  material, as well as for the extra distance traveled by the wave traveling down and back through the film. With the oil film example, constructive interference will occur if the film thickness is  $1/4$  wavelength,  $3/4$  wavelength,  $5/4$ , etc. Destructive interference occurs when the thickness of the oil film is  $1/2$  wavelength,  $1$  wavelength,  $3/2$  wavelength, etc.**



<http://physics.bu.edu/py106/notes/Thinfilm.html>

Light reflecting from the bottom surface of the oil film has no phase change, but it travels an extra distance of half the wavelength of red light. Red light reflected from the top surface interferes constructively with red light from the bottom surface, so the film looks red. Light of other colors experiences destructive interference.

5) How is a reddish color produced in the interference pattern? Bluish color?

**When the thickness of the nail polish is a half-wavelength of blue light thick, then blue light from the front and back surfaces will be out of phase and will not reflect. At this same thickness red light will be in-phase and will reflect strongly giving the reflected light a reddish color. (Half a wavelength of blue light in the nail polish is about 250 nm.)**

**When the thickness is a half-wavelength of red light then red will not reflect but blue will giving the reflected light a bluish color. (Half a wavelength of red light in the nail polish is about 450 nm.)**

# INTERFERENCE AND DIFFRACTION OF LIGHT

PHYSICS TEAM TRIVIA

**1) Projected on a screen is a two-slit interference pattern, the fringes are evenly spaced on the screen**

- ▶ **A) Only for small angles**
- ▶ **B) Only for large angles**
- ▶ **C) Only at  $45^\circ$**
- ▶ **D) never**

**2) Which of the following is a monochromatic and coherent light source?**

- ▶ **A) LED**
- ▶ **B) Fluorescent**
- ▶ **C) Laser**
- ▶ **D) Incandescent**

**3) Which is not a type of hologram that was discussed?**

- ▶ **A) refraction**
- ▶ **B) transmission**
- ▶ **C) pulsed**
- ▶ **D) embossed**

## 4) What is the function of a spectrometer?

- ▶ A) To eliminate light dispersion
- ▶ B) To reduce constructive interference
- ▶ C) To separate light from a source into its monochromatic components
- ▶ D) To produce coherent light

5) All lasers use a substance called the \_\_\_\_\_ to which energy is added to produce coherent light.

- ▶ A) Gas-ion barrier
- ▶ B) Stimulated emission
- ▶ C) Photon beam
- ▶ D) Active medium

## 6) Instruments that have high resolution are created to

- ▶ A) Reduce interference
- ▶ B) Eliminate coherence of light waves
- ▶ C) Enhance dispersion
- ▶ D) Maximize diffraction patterns

7) In a double slit experiment, the angle between the central maximum and the second bright fringe is  $2^\circ$ . The slit separation is  $3.8 \times 10^{-5} \text{ m}$ . What is the wavelength of the light source?

- ▶ A)  $5.3 \times 10^{-7} \text{ m}$
- ▶ B)  $6.6 \times 10^{-7} \text{ m}$
- ▶ C)  $5.9 \times 10^{-8} \text{ m}$
- ▶ D)  $6.4 \times 10^{-8} \text{ m}$

8) To meet the needs to form an interference pattern a(n) \_\_\_\_\_ is usually used as a light source.

- ▶ A) Halogen bulb
- ▶ B) Mercury vapor lamp
- ▶ C) Laser
- ▶ D) Light Emitting Diode

## 9) Which of the following changes would increase the resolution of a telescope?

- ▶ A) Observing light at a low wavelength, increasing the aperture
- ▶ B) Observing light at a low wavelength, decreasing the aperture
- ▶ C) Observing light at a high wavelength, increasing the aperture
- ▶ D) Observing light at a high wavelength, decreasing the aperture

**10) The inelastic scattering (KE is not conserved) of a photon is called**

- ▶ **A) Rayleigh Scattering**
- ▶ **B) Tyndall Scattering**
- ▶ **C) Raman Scattering**
- ▶ **D) Mie Scattering**

# INTERACTIVE WEBSITES FOR OPTICS

- 1) Great collection of optics websites  
<http://osa.magnet.fsu.edu/overload/>
- 2) Great for color mixing and spectral analysis of stars  
[http://www.learner.org/teacherslab/science/light/color/spectra/spectra\\_1.html](http://www.learner.org/teacherslab/science/light/color/spectra/spectra_1.html)  
alien eyes activity;
- 3) Snell's Law and total internal reflection  
<http://phet.colorado.edu/en/simulation/bending-light>
- 4) A lot of optic demo and lab ideas  
[http://www.teach-nology.com/teachers/lesson\\_plans/science/physics/waves/](http://www.teach-nology.com/teachers/lesson_plans/science/physics/waves/)
- 5) Microscopes  
<http://micro.magnet.fsu.edu/primer/anatomy/anatomy.html>
- 6) FAQ on lasers  
<http://www.phys.vt.edu/~jhs/faq/light.html>
- 7) Atmospheric optics  
<http://www.atoptics.co.uk/>
- 8) Rainbows  
<http://www.geom.uiuc.edu/education/calc-init/rainbow/>
- 9) Polarization  
<http://www.polarization.com/index-net/>
- 10) Physics tutorials  
<http://cpphysics.homestead.com/lightt.html>
- 11) Laser light show demo  
<http://osa.magnet.fsu.edu/teachersparents/classroomactivities/pdfs/create%20your%20own%20laser%20show.pdf>
- 12) Fun project ideas  
[http://www.funsci.com/texts/index\\_en.htm](http://www.funsci.com/texts/index_en.htm)
- 13) Electromagnetism – good NASA intro (electromagnetic spectrum song not that great, but maybe students could come up with a better one; the ROY G. BIV song by They Might be Giants is pretty cute – the website that this is linked to has quite a list of songs but mainly on topics that are for younger students)  
<http://mail.colonial.net/~hkaiter/electromagspectrum.html>

- 14) Microscope imaging site  
<http://www.exploratorium.edu/imaging-station/>
- 15) Rainbows explained  
<http://www.sixtysymbols.com/videos/rainbows.htm>
- 16) Video collection of Science Professors at Nottingham University explaining different physics topics  
<http://www.sixtysymbols.com/>
- 17) Biographies of famous scientists  
<http://www.famousscientists.org/>
- 18) Vision site  
<http://www.eyes-and-vision.com/just-for-fun.html>
- 19) Nuclear physics  
<http://www2.lbl.gov/abc/>
- 20) Cool Site by NASA (under games they have an IR magnifier)  
<http://spaceplace.nasa.gov/>
- 21) Main microscope site  
<http://micro.magnet.fsu.edu/primer/>