Remote Sensing, EET 3132
Lecture 1

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Remote Sensing

- What is Remote Sensing?
- What are the applications of the Remote Sensing field?
- Which are the industries interested in Remote Sensing?
- What are the potential jobs in Remote Sensing field?
- Course website: http://openlab.citytech.cuny.edu/remote_sensing/

Remote Sensing as an Information Source

Remote sensing has been defined as the science (and to some extent art) of acquiring information without actually being in contact with it. Applications of remote sensing information usually fall into one of the following categories:

1. Remote sensing is used as a tool to measure properties or conditions of the land, oceans, atmosphere or objects in space.
2. Images of remotely sensed information serve as base maps on which other information is overlaid for reference and enhanced interpretation.
3. Images of remotely sensed information are used to map and quantify the spatial distribution of features.
4. Multitemporal images can be compared to quantify changes in the area and spatial distribution of features.

Remote sensing advantages over traditional data sets

- it is unobtrusive;
- one can collect information simultaneously over a broad range of the electromagnetic spectrum;
- it is capable of making biophysical measurements; information can be acquired through clouds at long wavelengths;
- data can be collected in a very short timeframe with aircraft platforms and frequently with satellite platforms;
- data collection procedures are systematic thereby eliminating sampling bias introduced in some investigations;
- and analysis methods are relatively robust, objective, and repeatable.
- This is not to say that remotely sensed data necessarily replaces existing data sets, but in many cases it provides supplemental information that can lead to improved assessments.

Applications of Remote Sensing

- Astronomical (Hubble Telescope, Very Large Array)
- Climate Change (Environmental monitoring, see the Dept. of Environmental Conservation, NOAA, Environmental Protection Agency, Dept of Energy, etc)
- Medical (Xray, Ultrasounds, etc)
- Military (surveillance and target detection, see Dept. of Defense, NASA)
- Communication systems (free space optical communications, wireless)
- Geoscience (natural hazards, earthquake and volcano monitoring etc)
- Transportation systems (GIS and aerial photography)
- Archeology (satellite images and aerial photography)
- And many more

Companies Interested in Hiring RS Graduates (just a few)

- NASA
- NOAA
- Raytheon
- Lockheed Martin
- Aerospace Corporation
- Decagon Devices
- PP Systems
- etc

- SSAI
- National Laboratories
- Northrop Grumman
- Jet Propulsion Laboratory
- National Geospatial-Intelligence Agency
- Booz Allen Hamilton
- Americas ALOS Data Node

Schools Offering Continuing Education in RS

- CCNY/CUNY
- SUNY
- University of Wisconsin
- Texas A&M
- University of Maryland Baltimore County
- Berkeley
- MIT
- Rochester Institute of Technology
- University of Kansas
- Columbia University

QC/CUNY
Northeastern University
John Hopkins University
Rice University

Princeton
NCAR
University of New Hampshire
University of Michigan
And many more, nation-wide.

Annual Rates by Grade and Step
Federal Wage System

Grade	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Step 10	WGI
1	17803	18398	18990	19579	20171	20519	21104	21694	21717	22269	552
2	20017	20493	21155	21717	21961	22607	23253	23899	24545	25191	646
3	21840	22568	23296	24024	24752	25480	26208	26936	27664	28392	728
4	24518	25335	26152	26969	27786	28603	29420	30237	31054	31871	817
5	27431	28345	29259	30173	31087	32001	32915	33829	34743	35657	914
6	30577	31596	32615	33634	34653	35672	36691	37710	38729	39748	1019
7	33979	35112	36245	37378	38511	39644	40777	41910	43043	44176	1133
8	37631	38885	40139	41393	42647	43901	45155	46409	47663	48917	1254
9	41563	42948	44333	45718	47103	48488	49873	51258	52643	54028	1385
10	45771	47297	48823	50349	51875	53401	54927	56453	57979	59505	1526
11	50287	51963	53639	55315	56991	58667	60343	62019	63695	65371	1676
12	60274	62283	64292	66301	68310	70319	72328	74337	76346	78355	2009
13	71674	74063	76452	78841	81230	83619	86008	88397	90786	93175	2389
14	84697	87520	90343	93166	95989	98812	101635	104458	107281	110104	2823
15	99628	102949	106270	109591	112912	116233	119554	122875	126196	129517	3321

- For industry multiply by 2

SALARY TABLE 2011-GS

RATES FROZEN AT 2010 LEVELS

Jobs in RS

- According to http://www.bls.gov/oco/ocos040.htm some of the jobs in the field of RS are:
  - RS Technician/Engineer/Scientist
  - Instrument Developer
  - Project management
  - Urban Regional Planner
  - Professor/ CLT
  - Surveyors and cartographers
  - Photogrammetrists,
  - Surveying technicians.

Bureau of Labor Statistics

- According to the Bureau of Labor statistics (BLS) (http://www.bls.gov/oco/ocos040.htm) the employment of surveyors, cartographers, photogrammetrists, and surveying technicians held about 147,000 jobs in 2008.
- The architectural, engineering, and related services industry—including firms that provided surveying and mapping services to other industries on a contract basis—provided 7 out of 10 jobs for these workers. Federal, State, and local governmental agencies provided about 15 percent of these jobs. Major Federal Government employers are the U.S. Geological Survey (USGS), the Bureau of Land Management (BLM), the National Oceanic and Atmospheric Administration, the U.S. Forest Service, and the Army Corps of Engineers. Most surveyors in State and local government work for highway departments or urban planning and redevelopment agencies. Utility companies also employ.
- According to this source the occupations in the remote sensing field should experience faster than average employment growth. The Employment of surveyors, cartographers, photogrammetrists, and surveying and mapping technicians is expected to grow 19 percent from 2008 to 2018, which is faster than the average for all occupations. Increasing demand for fast, accurate, and complete geographic information will be the main source of job growth.
- Environmental scientists and specialists held about 85,900 jobs in 2008. An additional 6,200 jobs were held by environmental science faculty. About 37 percent of environmental scientists were employed in State and local governments; 21 percent in management, scientific, and technical consulting services; 15 percent in architectural, engineering and related services; and 7 percent in the Federal Government, primarily in the Environmental Protection Agency (EPA) and the Department of Defense.

- https://ngc.taleo.net/careersection/ngc_coll/jobdetail.ftl
- Co-Op Technical   Co-Op   **Requisition ID**: 11016235
- **Location(s)** : United States-California-Woodland Hills   **Business Sector** : Electronic Systems
- **US Citizenship Required for this Position**:Yes   **Relocation Assistance**: No relocation assistance available
- **Description** Developing leading-edge navigation solutions with fiber-optic technology, integrating "all glass cockpits" that help the warfighter in any weather, day or night. Improving the state-of-the art sensors and radars. Success stories like these are why Northrop Grumman, Navigation Systems Division (NSD) is an industry leader. If you're searching for a career where you can be part of a larger-than-life achievement, take a look at everything we have to offer.
- Northrop Grumman Electronic Systems sector is seeking a College Technical Co-Op to join our team of qualified, diverse individuals. This position will be located in Woodland Hills, California. The Woodland Hills campus is situated on over 50 acres, has an on-site cafeteria, softball field, basketball courts, and offers a friendly work environment. In addition, this site follows an alternative, 9/80 workweek schedule for most positions.
- Performs a variety of duties in the electronic, mechanical, electromechanical, or optical areas. Constructs, troubleshoots, calibrates, adjusts, tests, and maintains equipment, components, devices, or systems. Works from engineering drawings and written or verbal instructions. Operates related equipment; conducts tests and reports data in prescribed format. Performs calibration and alignment checks; makes adjustments, modifications, and replacements as directed; prepares prescribed compounds and solutions. Exclude technicians working in Production or Quality Assurance.
- **Basic Qualifications:**
  Candidate should be enthusiastic, "can do" person, willing to take on any and all challenges and able to establish comprehensive plans for executing assignments. Candidate should have a good foundation in electronic fundamentals and must be able to demonstrable experience in a lab environment, building and testing electronic devices to support engineering.
- Candidate should have good written and verbal communication skills and be a "team player". Candidate should have a minimum ASEE or equivalent schooling. Candidate must be pursuing a Bachelors in Electrical Engineering.
- **Preferred Qualifications:**
  Previous internship experience and have taken some upper division courses within the Electrical Engineering curriculum.

Example of job requirement

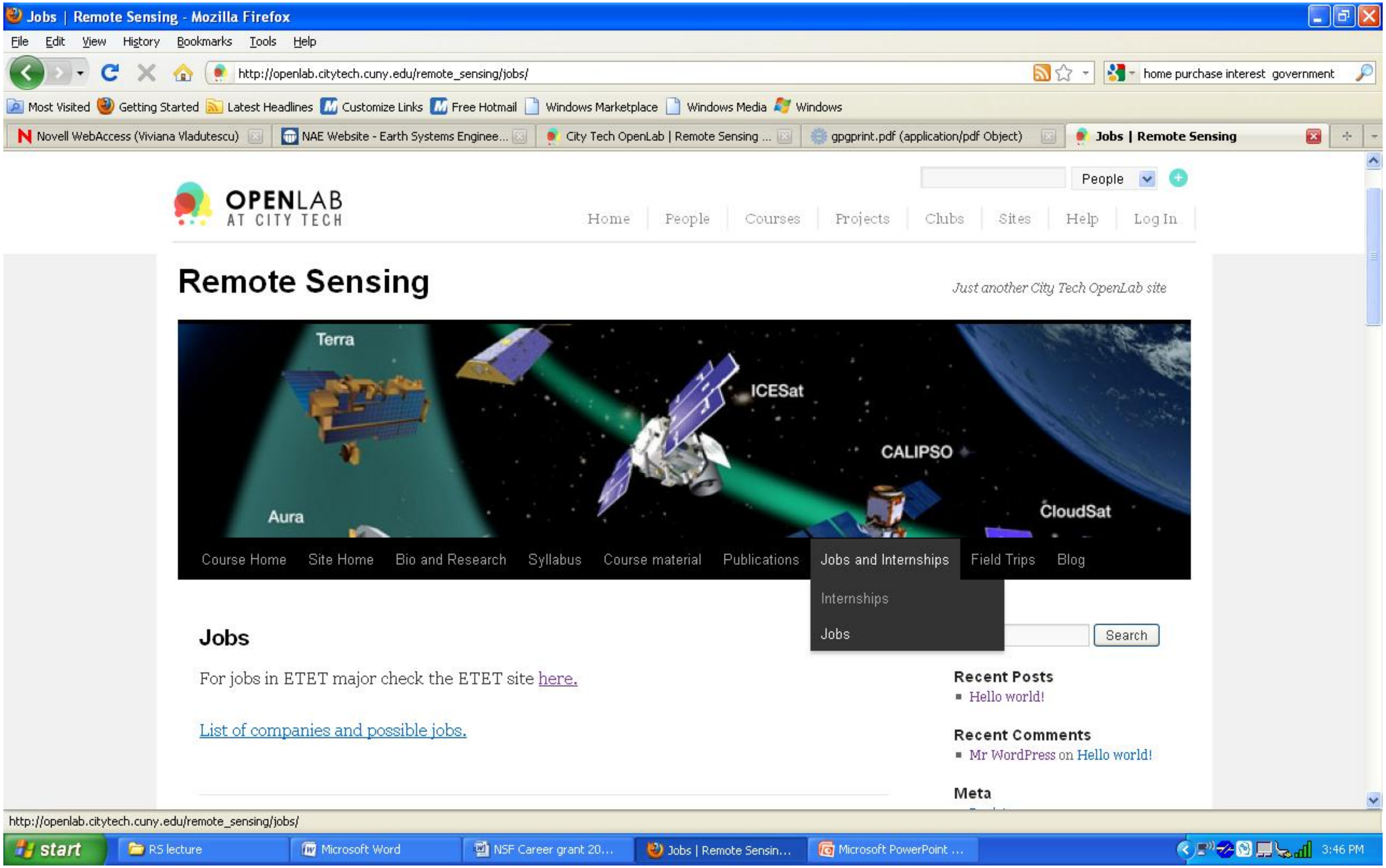
https://www.aerospace.apply2jobs.com/ProfExt/index.cfm?fuseaction=mExternal.showJob&RID=3704&CurrentPage=10&sid=135

- Job Title: Remote Sensing Intern - Graduate Requisition #: 3704
  Group: Engineering and Technology Group
  Department: ADVANCED SENSOR ENGINEERING DEPT
  Clearance Required: SSBI
  Duties: Perform various hardware prototyping, interface tasks or algorithm development tasks for remote sensing applications. Tasks may include laboratory electronics, 3D design, computer coding, testing, and documenting various tests and experiments. Work with members of the staff as part of an effective team. Duties will also include documentation of work and occasional presentations.

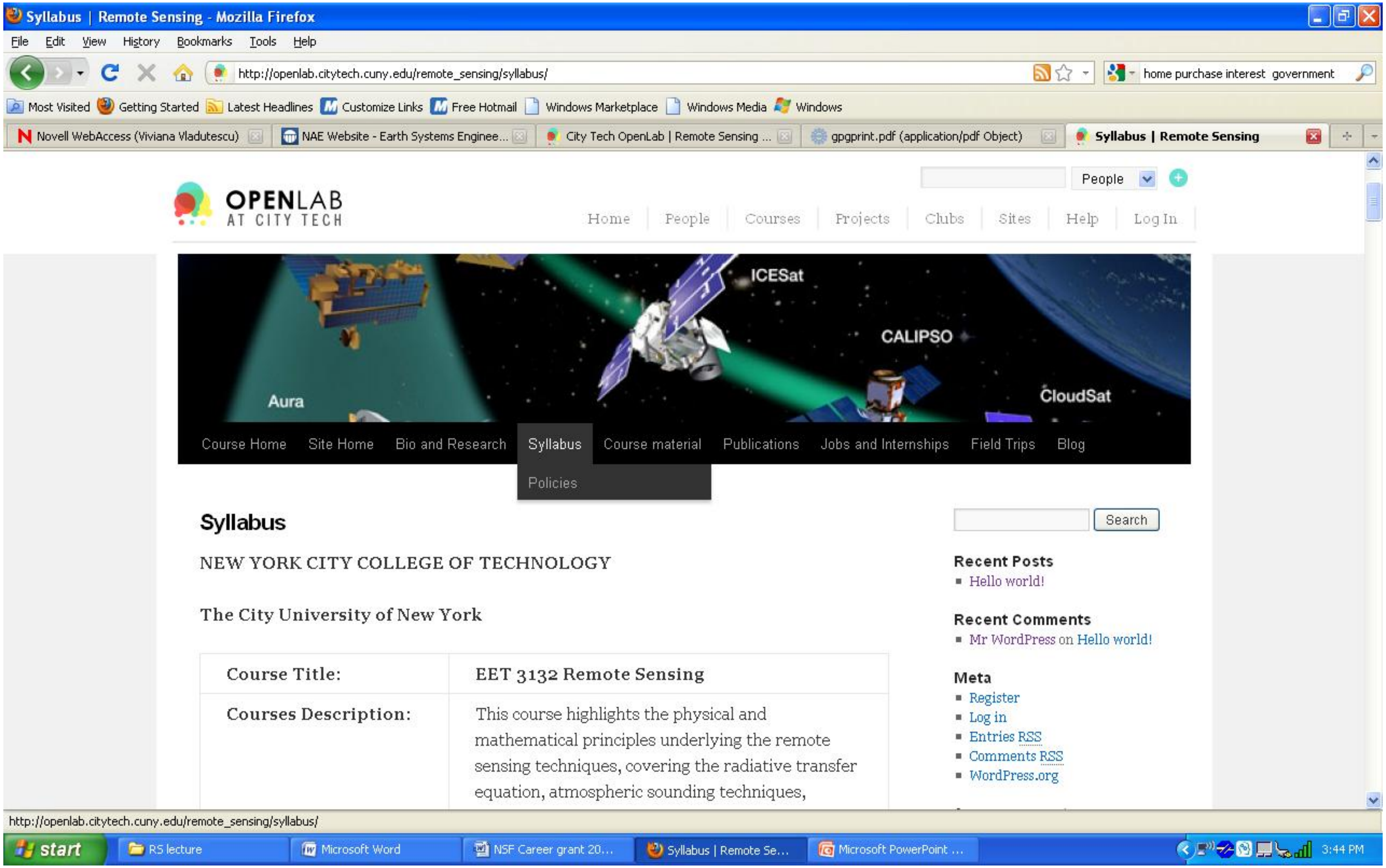
  Qualifications: Bachelors degree students in physics, mathematics, electrical engineering; related disciplines will be considered. Excellent academic standing, some research experience and strong verbal/written communications skills. Ability to work independently as well as within a team. Computer proficiency with common engineering programming languages (e.g., Matlab, C, Java). Current Top Secret/SSBI, or the ability to obtain one, is required.

  Recruiter: GRAHAM-WADDELL, MARY
  Interest Category: Engineer
  State: Virginia
  City: Chantilly

Remote Sensing Website



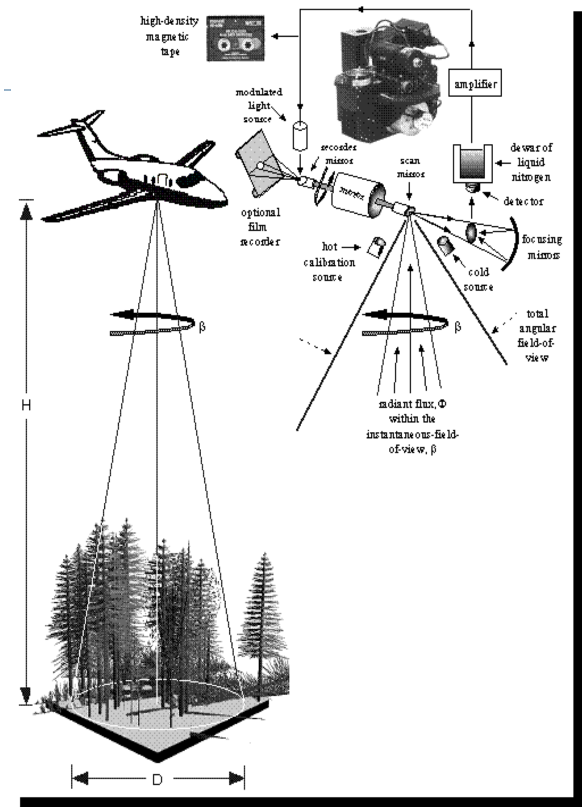
EET 3132 Syllabus

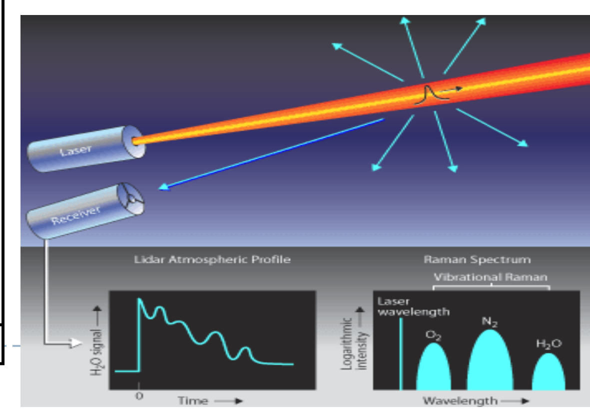


http://openlab.citytech.cuny.edu/remote_sensing/

Remote Sensing Course

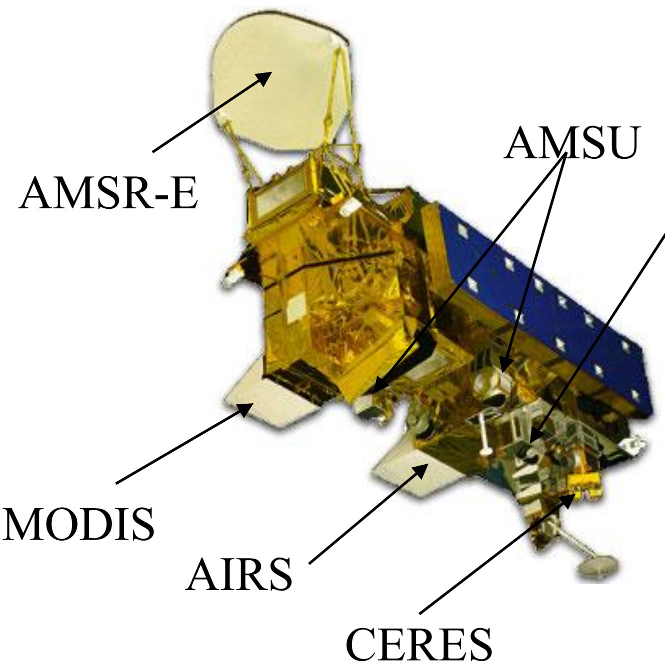
Course Title:	**EET 3132 Remote Sensing**
Courses Description:	This course highlights the physical and mathematical principles underlying the remote sensing techniques, covering the radiative transfer equation, atmospheric sounding techniques, interferometric and lidar systems, and an introduction to image processing. The lab component will introduce remote sensing software HYDRA, and MATLAB which will be used for image display and data analysis.
Credit hours:	3 course credits, consisting of 2 classroom hours, and 2 Lab hours
Prerequisites:	Calculus I (MAT 1475), Physics 2.2 (PHYS 1434) or Physics 2.3 (PHYS 1442)
Required text:	1. Remote Sensing from Air And Space by R. C. Olsen, SPIE Press, 2007
Supplemental texts:	[1]G. L. Stephens, *Remote sensing of the lower atmosphere. An Introduction*, Oxford University Press, NY, USA 1994 [2] R. Measures, *Laser Remote Sensing: Fundamentals and Applications,* Krieger Publishing Company, Reprint Edition,1992 [3] V. Kovalev et.al, *Elastic Lidar, Theory, practice, and analyses methods,* John Wiley and sons, New Jersey, USA 2004 [4] H.C. van de Hulst, *Light Scattering by Small Particles,* Dover Publications, NY, 1981 [5] Hecht E.; "*Optics", 3rd Ed.* Addison Wesley, 1998
Prepared by:	Viviana Vladutescu





Objectives and Assessment

INSTRUCTIONAL OBJECTIVES	ASSESSMENT
For the successful completion of this course, the students should be able to:	Evaluation Methods and Criteria: Students will exhibit skills in class discussion, homework assignments, laboratory exercises, quizzes, exams, and course projects.
1. Describe the distribution of radiation in Earth's atmosphere	1. Students will demonstrate skills in solving radiative transfer equations using numerical methods
2. Describe the atmospheric sounding techniques	2. Students will prove their ability of using kernel functions for retrieval of different atmospheric parameters at different altitude levels
3. Understand the impact that electro optical systems have on remote sensing, obtain atmospheric vertical profiles and interpret the results	3. Students will be able to describe different electro-optical systems and corresponding applications. Students will be able to describe lidar systems and corresponding applications and calculate vertical backscatter and extinction profiles.
4. Analyze optical properties and concentrations of atmospheric trace constituents	4. Students will be able to identify spectral signatures of atmospheric constituents and determine concentrations based on mixing ratios or absorptions of radiation in the corresponding absorption window. Students will also be able to perform the correct measurements using the instrumentation pertaining to the analysis of the atmospheric components of interest.
5. Describe the standard orbits and calculate orbital elements	5. Students will be able to identify the different satellites and their sensors on board along with their applications
6. Derive data from remote sensing systems and incorporate them in initialization and validation of forecast models.	6. Students will be able to manipulate statistical and software techniques (Matlab, IDL or Hydra) for model development



Grading Procedure:	
Midterm	15%;
Project	25%;
Laboratory	30%
Final Exam	30%

Syllabus

Week	Topic	Reading assignments	Homework	laboratory Assignments
1	**Electromagnetics basis** Electromagnetic waves, polarization, spectra and Fourier transform, the Doppler effect, angular distribution of radiation, thermal radiation, diffraction	Pg. 33-45	Problems 1-4/ Pg 29, Problems 1-5 / Pg 53.	**Lab 1:** Online remote sensing data resources (Aeronet, Hysplit, NASA, NOAA, etc). Analysis of the downloaded data using Matlab program.
2	**Interaction of electromagnetic radiation with matter** Propagation through homogeneous materials, Plane boundaries, volume scattering, reflection and emission from real materials	Pg. 48-53	Problems 6-10 /Pg 53.	**Lab 2:** HYDRA software used for data processing and image display. HYDRA Commands.
3	**Interaction of electromagnetic radiation with earth atmosphere** Molecular absorption and scattering, microscopic particles, large particles, radiative transfer equation, propagation through the atmosphere	Pg. 63-70	Problems 1-10 / Pg. 101	**Lab 3:** Field trips, Internet data downloading
4	**Electro optical remote sensing system** **Spectral Imagery** VIR imaging systems, Thermal infrared imagers, Atmospheric sounding	Pg. 157-170	Problems 1-4 /Pg 178	**Lab 4:** Interferometer Measurements of Atmospheric Absorption
5	**Orbital mechanics** Gravitational force, circular motion, satellite motion	Pg. 103-115	Problems 1-7 / Pg 115	**Lab 5:**Calculation of satellite motion, circular motion, orbital elements and standard orbits
6	Remote Sensing of the Earth's surface and **atmosphere** General considerations, Projects assignments	Pg. 117-127	Problems 1-5 / Pg 136	**Lab 6:**Using HYDRA to Inspect Multispectral Remote Sensing Data EXAM
7	Remote Sensing of the Earth's surface and **atmosphere** (e.g. ocean color, snow/ice,	Pg.127-136, Handouts	Problems 6-10 / Pg 136	**Lab 7:** Analyzing MODIS data viewing land, ocean, and atmosphere
8	**Clouds, SST, and Moisture Sensed with MODIS** Cloud masking, sea surface temperature algorithms,	Handouts	Handout problems	**Lab 8 :** Understanding Multispectral Cloud Properties sensed with MODIS
9	**Investigations with High Spectral Resolution Sounders** Atmospheric trace gases, absorption features over water and over clouds. On-band and off-band investigations	Handouts	Handout problems	**Lab 9 :** Staging, Viewing, and Interrogating AIRS Data
10	**Spectral Signatures seen with AIRS** Spectral signature of opaque clouds, temperature profiles, contrast	Handouts	Handout problems	**Lab 10** – Exploring Spectral Properties of Clouds, Moisture, and Volcanic Ash Sensed with AIRS
11	**Ranging Systems** Laser profiling, Radar altimetry laser remote-sensor system	Pg. 179-208	Problems 1-6 / Pg 208	**Lab 11:** Field Trips
12	**Scattering Systems** Lidar equation, radar equation, DIAL equation, geometry of receiver optics, solution of the lidar equation	Pg. 211-218	Problems 1 / Pg 224, Handouts,	**Lab 12:** LIDAR systems and vertical profiles (Using Matlab software)
13	**Atmospheric Lidar applications** Atmospheric studies, spaceborne lidar operation,	Pg. 218-224	Handouts (Matlab codes)	**Lab 13:** LIDAR backscatter and extinction profiles (Matlab)
14	**Data Processing** Transmission and storage of data , image processing **Atmospheric models** Climate models, community models, weather prediction forecast models WRF, CDAS http://www.ncar.ucar.edu/tools /models/modelslist.php , http://wrfmodel.org/users/users.php, http://cdaweb.gsfc.nasa.gov/	Pg. 137-156	Problems 1-5 / Pg 156 Handouts	**Lab 14:** Elements of recognition (shape, size, shadow, height, etc), filters, histograms (Matlab)
15	FINAL EXAM		Project presentations	

Capstone Project

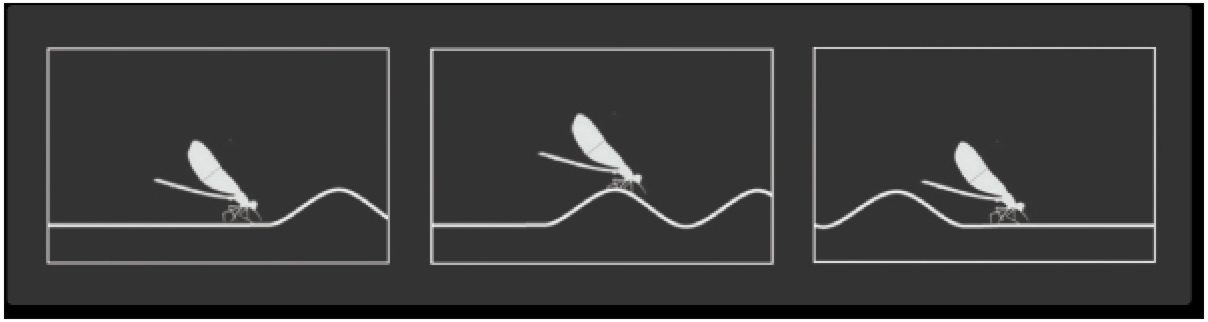
The Remote Sensing Capstone Project is multi-disciplinary and encompasses theoretical, laboratory and field studies using data from different fields and instruments like land instruments, satellite thermal infrared, imaging spectroscopy, lidar, microwave systems, etc. The students involved in these projects will be focused on collecting and analyzing remotely sensed data in conjunction with in situ measurements to demonstrate the power of integrating the two to derive information on the land, ocean and atmospheric parameters. Students will also be involved in new instrument designs and manufacturing. The project coordinators will provide and maintain common facilities and hardware for data acquisition, analysis and interpretation and provide frameworks for investigations which are in early stages of development and testing with open end solutions.

Review of Physics

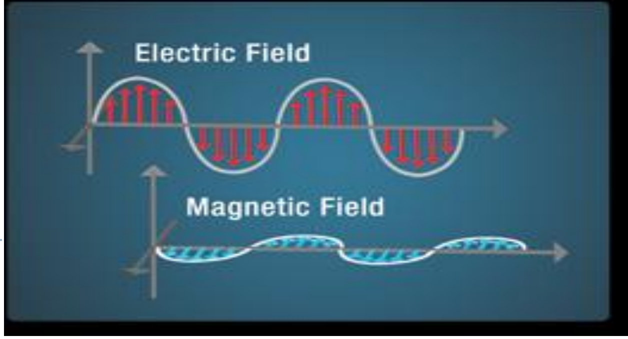
Waves- Mechanical

- Mechanical waves and electromagnetic waves are two important ways that energy is transported in the world around us. Waves in water and sound waves in air are two examples of mechanical waves.
- Mechanical waves are caused by a disturbance or vibration in matter, whether solid, gas, liquid, or plasma. Matter that waves are traveling through is called a medium. Water waves are formed by vibrations in a liquid and sound waves are formed by vibrations in a gas (air).
- These mechanical waves travel through a medium by causing the molecules to bump into each other, like falling dominoes transferring energy from one to the next. Sound waves cannot travel in the vacuum of space because there is no medium to transmit these mechanical waves.

- Classical waves transfer energy without transporting matter through the medium. Waves in a pond do not carry the water molecules from place to place; rather the wave's energy travels through the water, leaving the water molecules in place, much like a bug bobbing on top of ripples in water.



Waves- Electromagnetic



- Electromagnetic waves differ from mechanical waves in that they do not require a medium to propagate. This means that electromagnetic waves can travel not only through air and solid materials, but also through the vacuum of space.
- In the 1860's and 1870's, a Scottish scientist named James Clerk Maxwell developed a scientific theory to explain electromagnetic waves. He noticed that electrical fields and magnetic fields can couple together to form electromagnetic waves. He summarized this relationship between electricity and magnetism into what are now referred to as "Maxwell's Equations."

Maxwell's Equations

We now have a complete set of equations that describe electric and magnetic fields, called Maxwell's equations. In the absence of dielectric or magnetic materials, they are:

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{Q}{\epsilon_0}$$

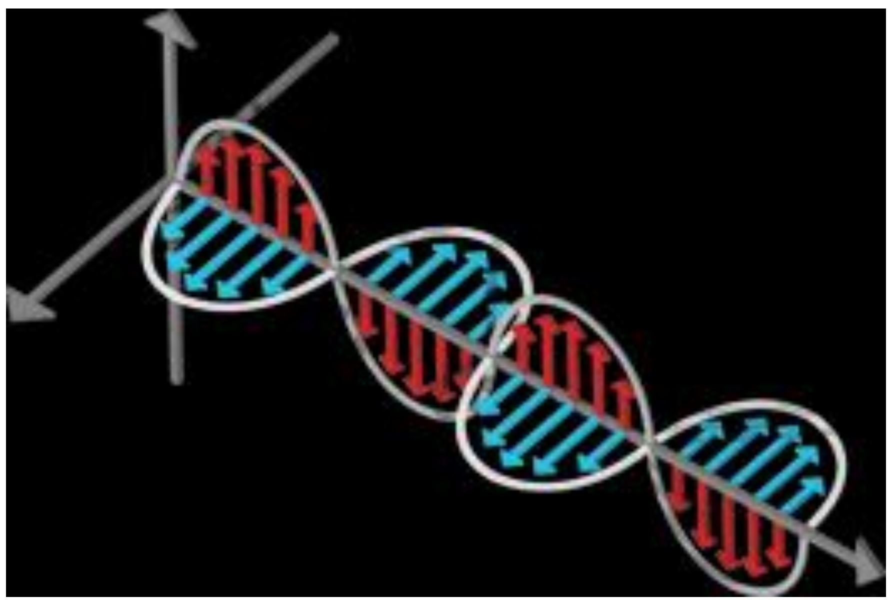
$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = 0$$

$$\oint \vec{\mathbf{E}} \cdot d\vec{\ell} = -\frac{d\Phi_B}{dt}$$

$$\oint \vec{\mathbf{B}} \cdot d\vec{\ell} = \mu_0 I + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}.$$

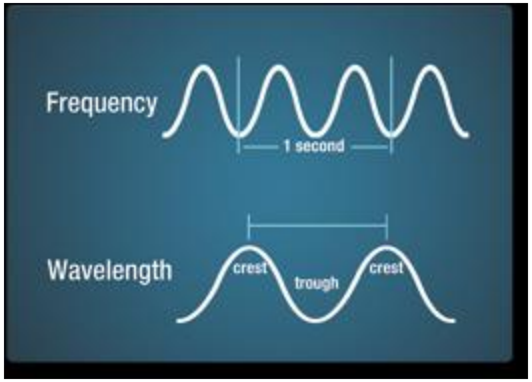
Electromagnetic waves

- Electromagnetic waves are formed by the vibrations of electric and magnetic fields. These fields are perpendicular to one another in the direction the wave is traveling. Once formed, this energy travels at the speed of light until further interaction with matter.



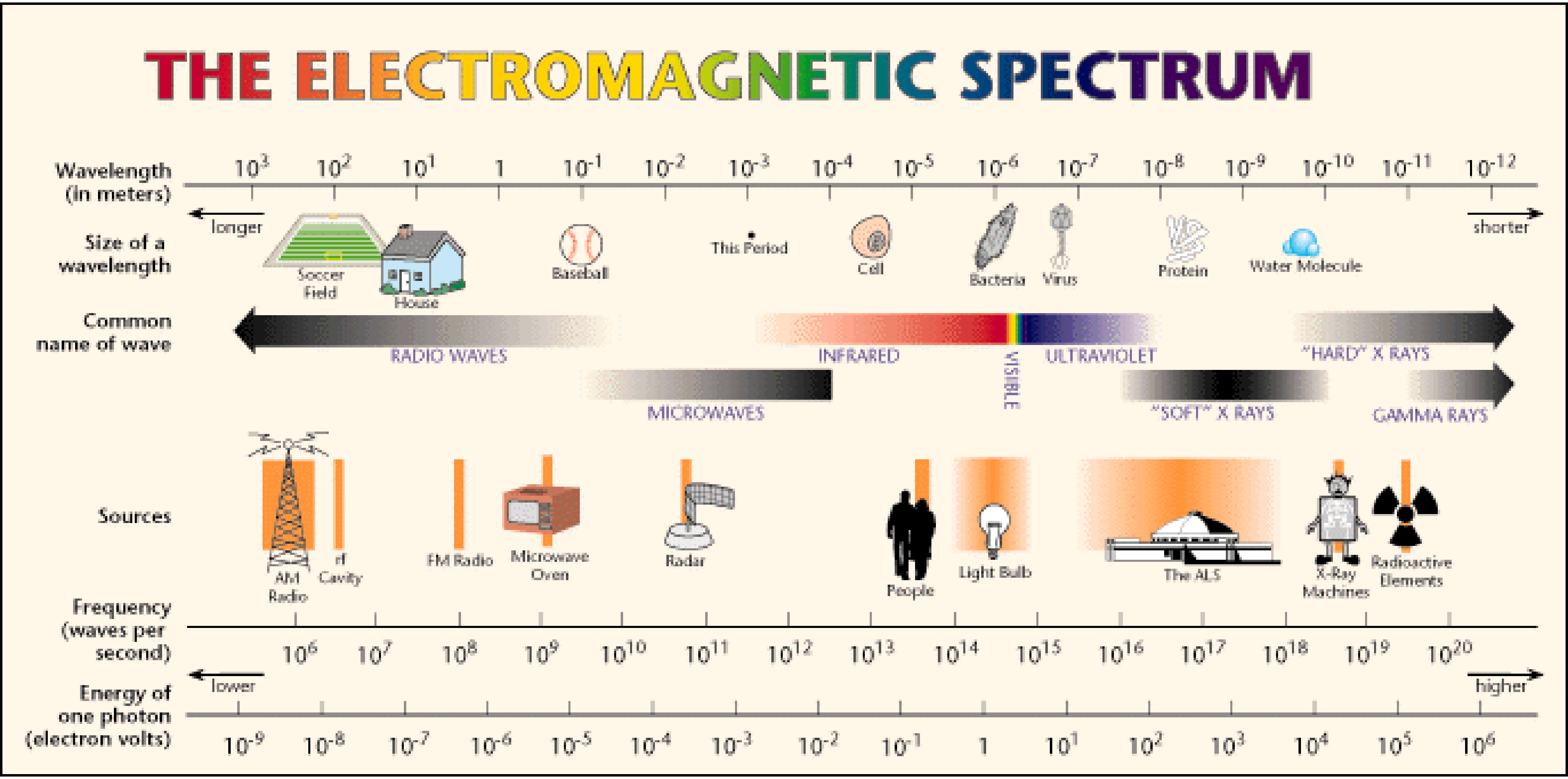
Frequency and Wavelength

- **FREQUENCY**
  - The number of crests that pass a given point within one second is described as the frequency of the wave. One wave—or cycle—per second is called a Hertz (Hz), after Heinrich Hertz who established the existence of radio waves. A wave with two cycles that pass a point in one second has a frequency of 2 Hz.



- **WAVELENGTH**
  - Electromagnetic waves have crests and troughs similar to those of ocean waves. The distance between crests is the wavelength. The shortest wavelengths are just fractions of the size of an atom, while the longest wavelengths scientists currently study can be larger than the diameter of our planet!

A few concepts in Electromagnetics



Light

- **WAVES OR PARTICLES? YES!**

- Light is made of discrete packets of energy called photons. Photons carry momentum, have no mass, and travel at the speed of light. All light has both particle-like and wave-like properties. How an instrument is designed to sense the light influences which of these properties are observed. An instrument that diffracts light into a spectrum for analysis is an example of observing the wave-like property of light. The particle-like nature of light is observed by detectors used in digital cameras—individual photons liberate electrons that are used for the detection and storage of the image data.

Energy?

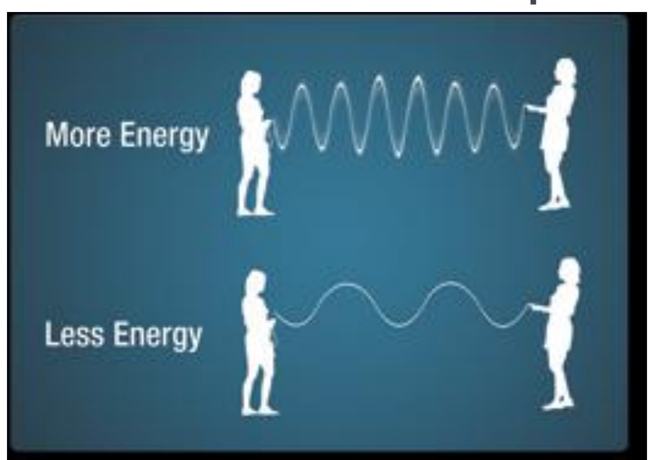
- Energy, a measure of the ability to do work, comes in many forms and can transform from one type to another. Examples of stored or potential energy include batteries and water behind a dam. Objects in motion are examples of kinetic energy. Charged particles—such as electrons and protons—create electromagnetic fields when they move, and these fields transport the type of energy we call electromagnetic radiation, or light.

ELECTROMAGNETIC ENERGY

- The terms light, electromagnetic waves, and radiation all refer to the same physical phenomenon: electromagnetic energy. This energy can be described by frequency, wavelength, or energy.
- All three are related mathematically such that if you know one, you can calculate the other two.
- Radio and microwaves are usually described in terms of frequency (Hertz), infrared and visible light in terms of wavelength (meters), and x-rays and gamma rays in terms of energy (electron volts).
- This is a scientific convention that allows the convenient use of units that have numbers that are neither too large nor too small.

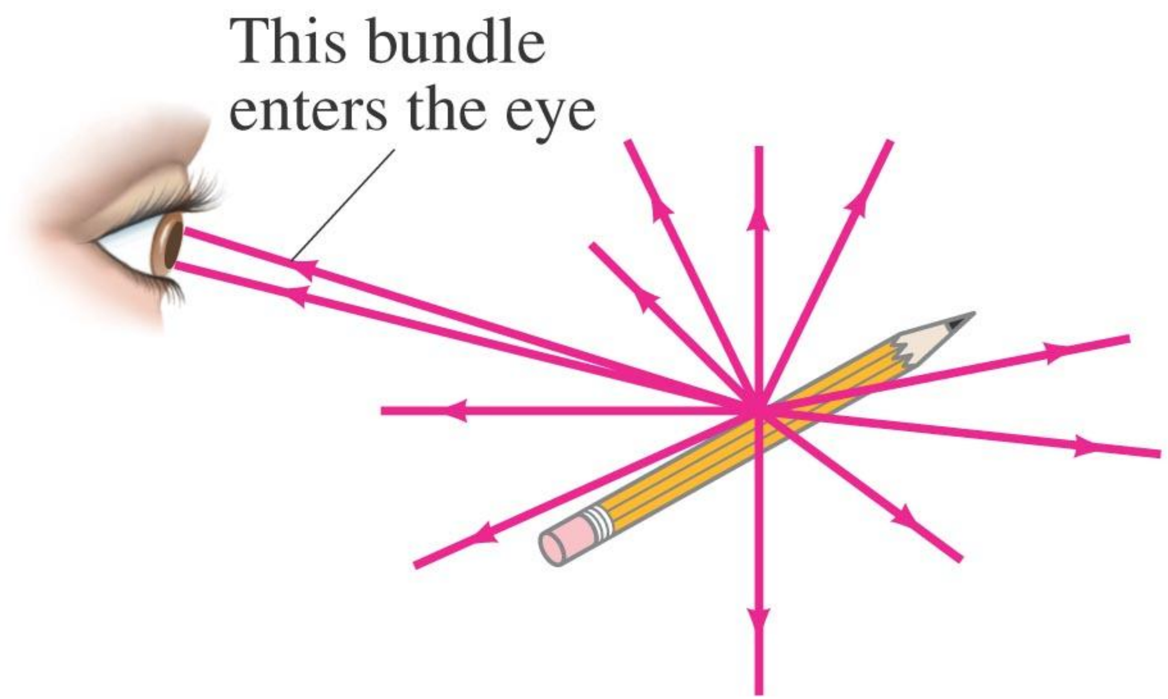
ELECTROMAGNETIC ENERGY cont'd

- **ENERGY**
  - An electromagnetic wave can also be described in terms of its energy—in units of measure called electron volts (eV). An electron volt is the amount of kinetic energy needed to move an electron through one volt potential. Moving along the spectrum from long to short wavelengths, energy increases as the wavelength shortens. Consider a jump rope with its ends being pulled up and down. More energy is needed to make the rope have more waves.



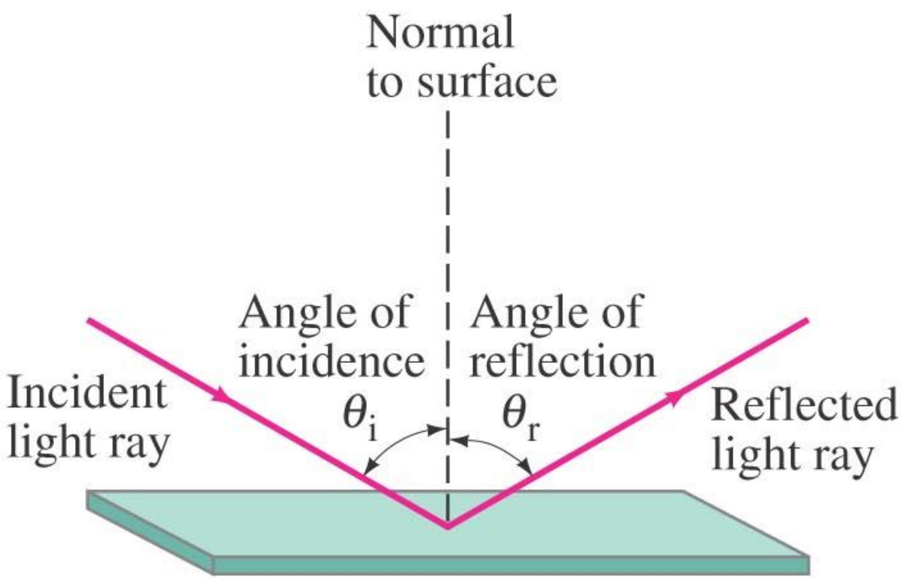
The Ray Model of Light

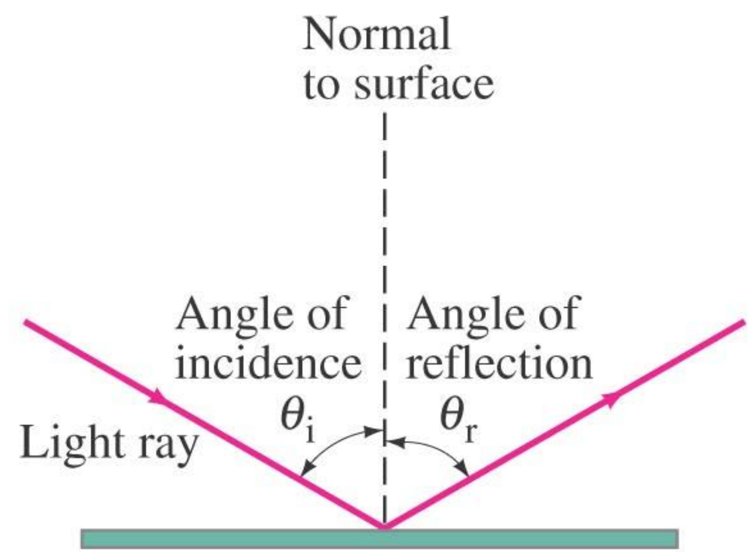
Light very often travels in straight lines. We represent light using rays, which are straight lines emanating from an object. This is an idealization, but is very useful for geometric optics.



Reflection; Image Formation by a Plane Mirror

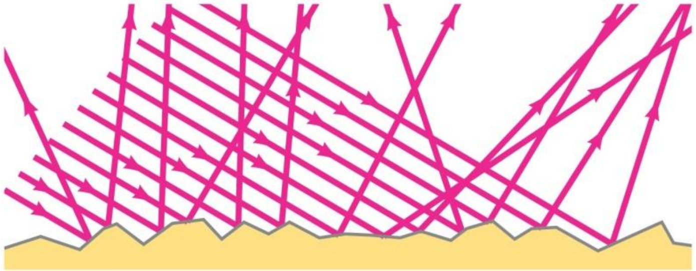
Law of reflection: the angle of reflection (that the ray makes with the normal to a surface) equals the angle of incidence.



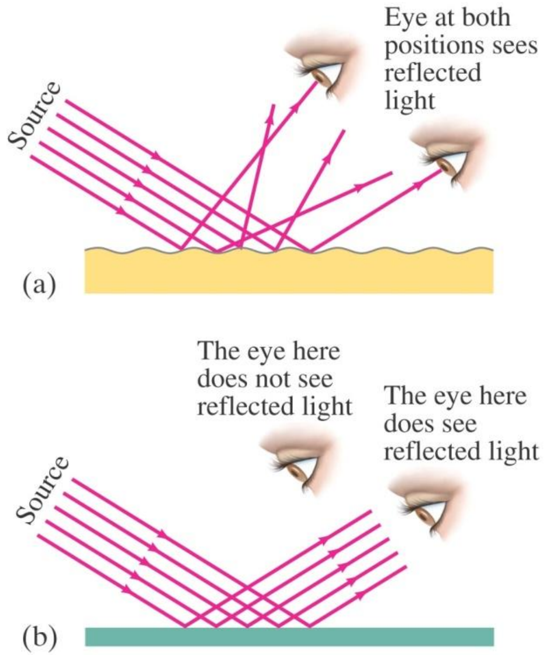


Reflection; Image Formation by a Plane Mirror

When light reflects from a rough surface, the law of reflection still holds, but the angle of incidence varies. This is called diffuse reflection.

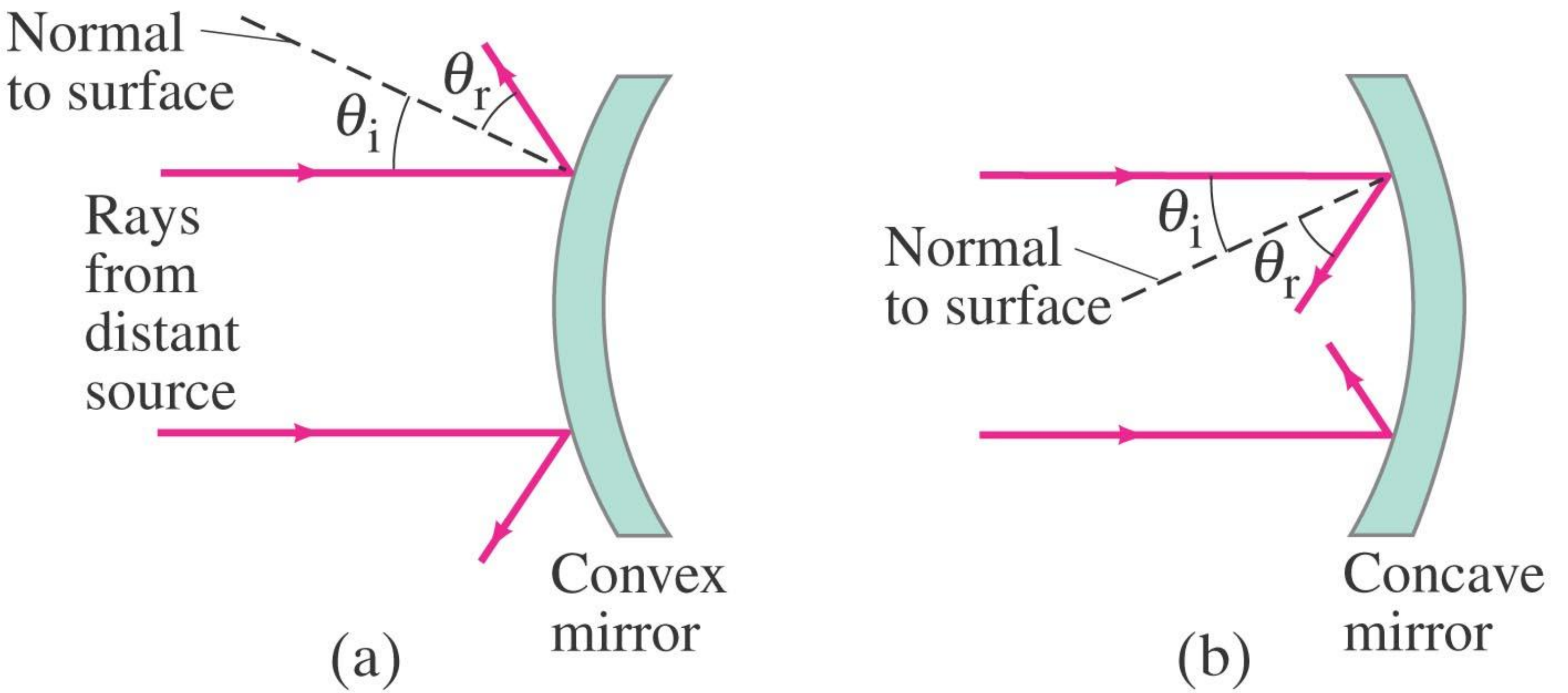


With diffuse reflection, your eye sees reflected light at all angles. With specular reflection (from a mirror), your eye must be in the correct position.



Formation of Images by Spherical Mirrors

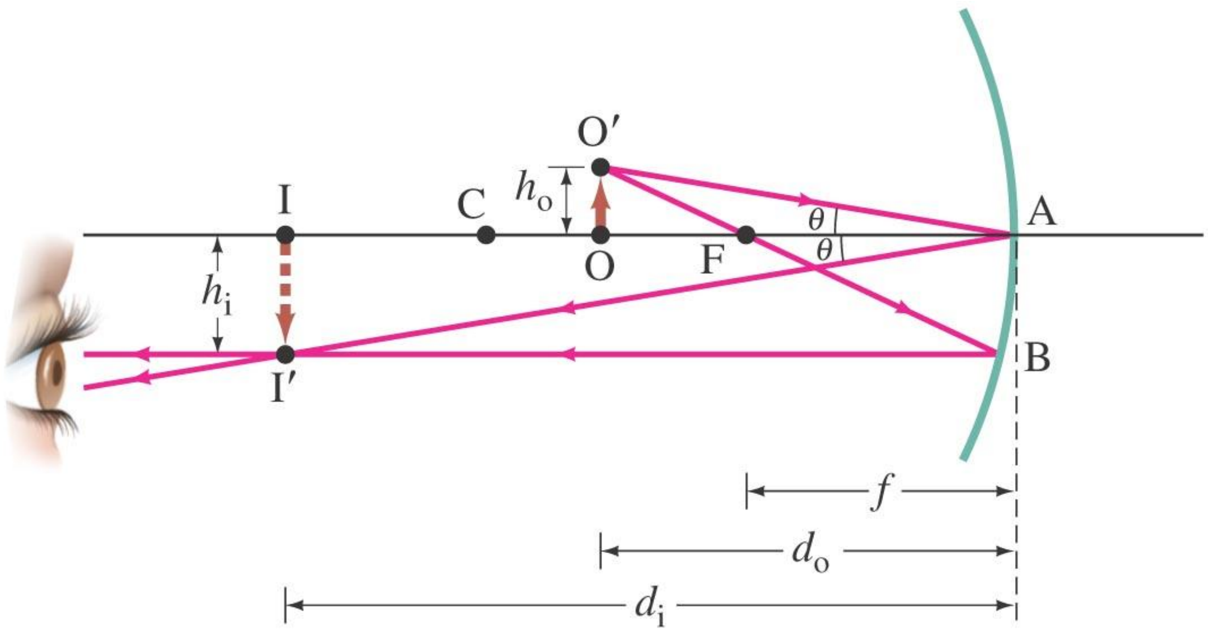
Spherical mirrors are shaped like sections of a sphere, and may be reflective on either the inside (concave) or outside (convex).



Formation of Images by Spherical Mirrors

Geometrically, we can derive an equation that relates the object distance, image distance, and focal length of the mirror:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}.$$



Formation of Images by Spherical Mirrors

We can also find the magnification (ratio of image height to object height):

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}.$$

The negative sign indicates that the image is inverted. This object is between the center of curvature and the focal point, and its image is larger, inverted, and real.

Index of Refraction

In general, light slows somewhat when traveling through a medium. The index of refraction of the medium is the ratio of the speed of light in vacuum to the speed of light in the medium:

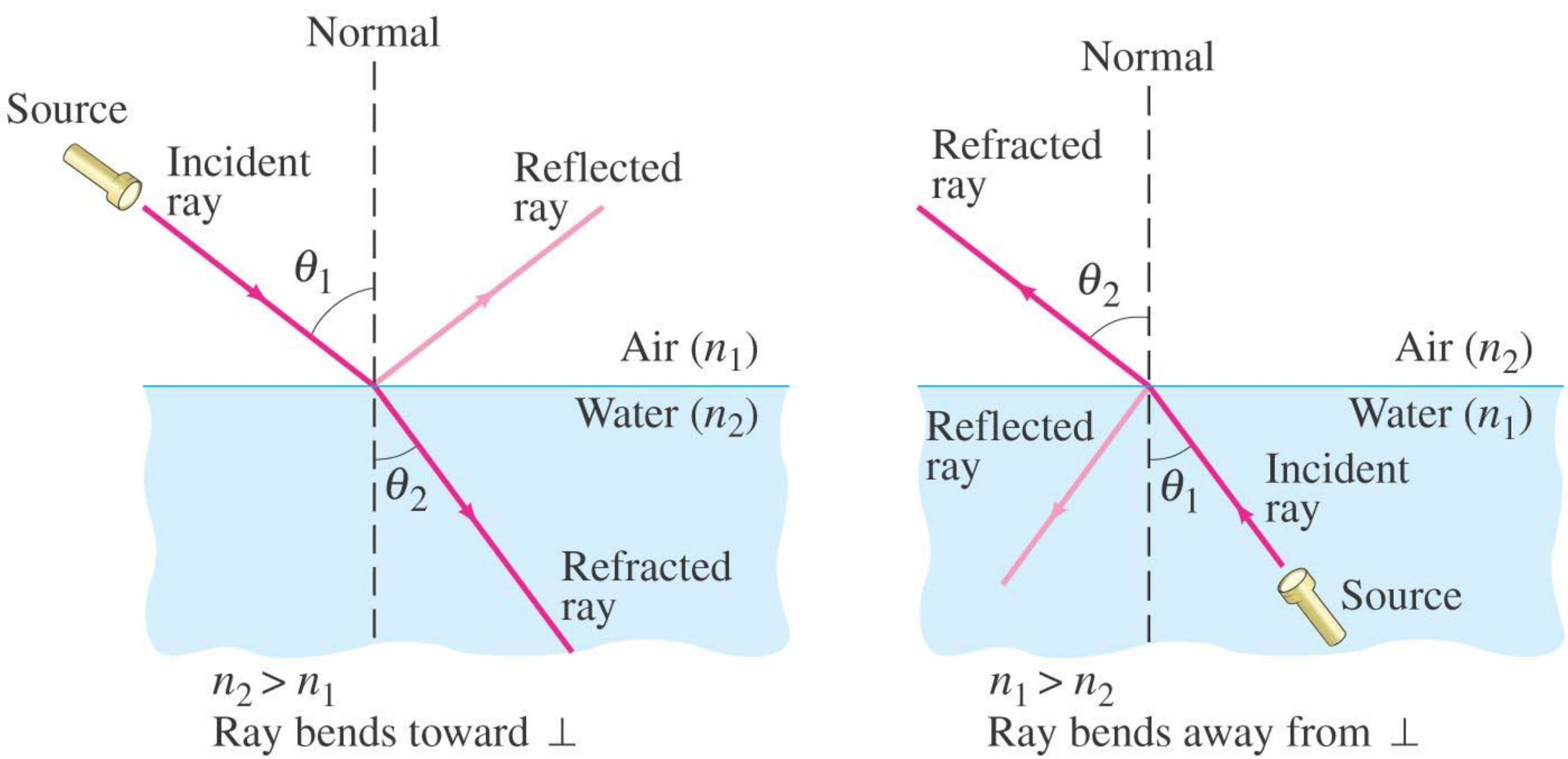
$$n = \frac{c}{v}.$$

Material	$n = \frac{c}{v}$
Vacuum	1.0000
Air (at STP)	1.0003
Water	1.33
Ethyl alcohol	1.36
Glass	
Fused quartz	1.46
Crown glass	1.52
Light flin	.58
Lucite or Plexiglas	1.51
Sodium chloride	1.53
Diamond	2.42

† $\lambda = 589$ nm.

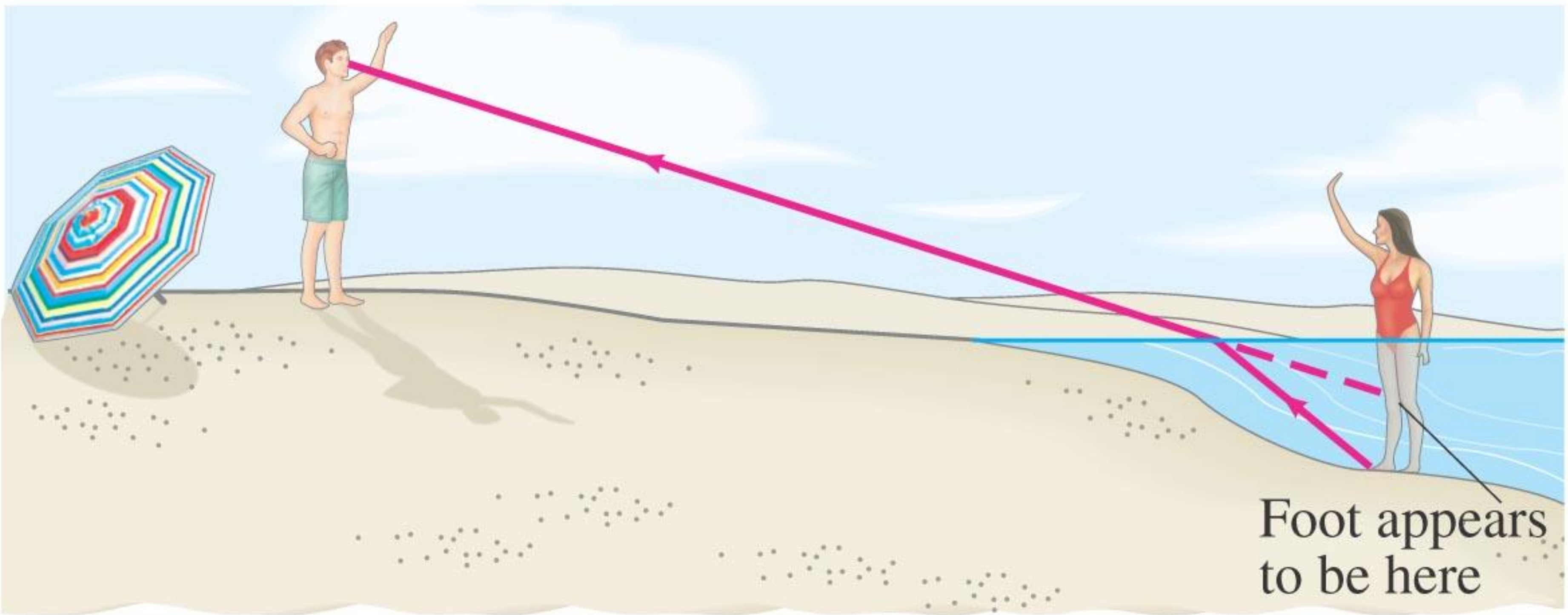
Refraction: Snell's Law

Light changes direction when crossing a boundary from one medium to another. This is called refraction, and the angle the outgoing ray makes with the normal is called the angle of refraction.



Refraction: Snell's Law

Refraction is what makes objects half-submerged in water look odd.



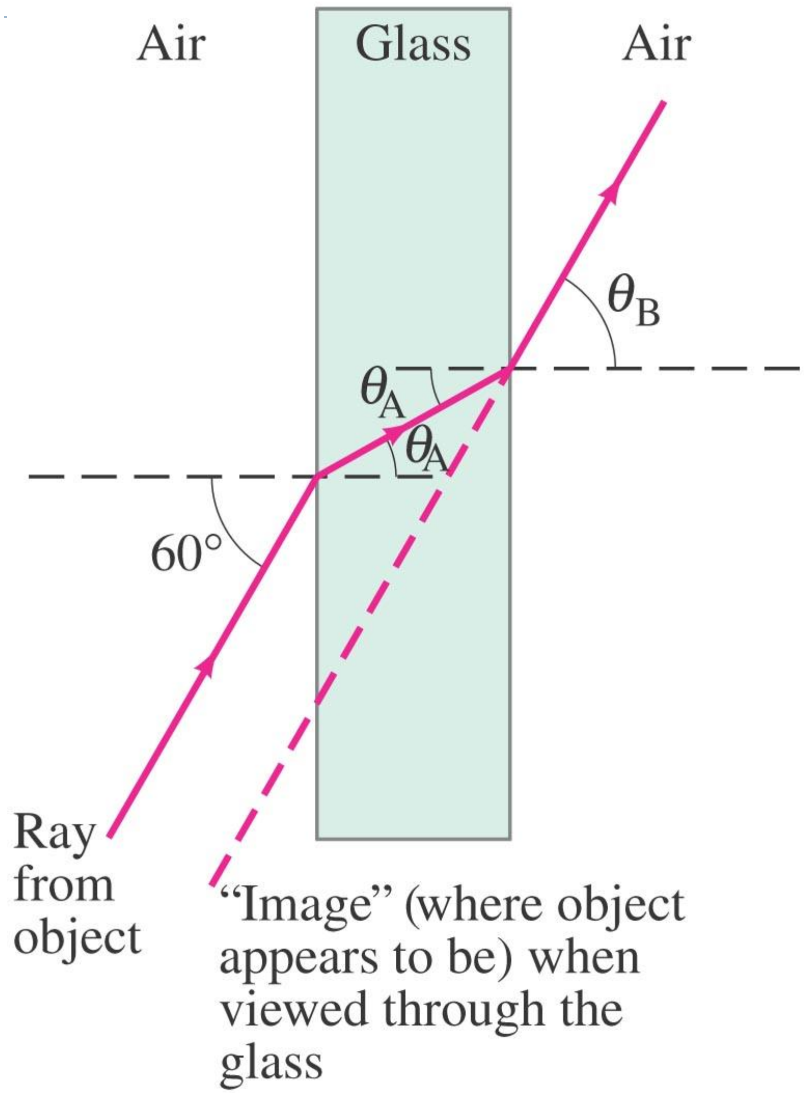
The angle of refraction depends on the indices of refraction, and is given by Snell's law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 .$$

Refraction: Snell's Law

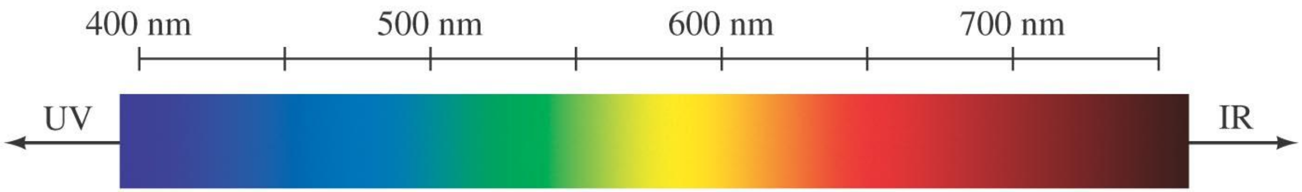
Example : Refraction through flat glass.

Light traveling in air strikes a flat piece of uniformly thick glass at an incident angle of 60°, as shown. If the index of refraction of the glass is 1.50, (a) what is the angle of refraction ϑ_A in the glass; (b) what is the angle ϑ_B at which the ray emerges from the glass?

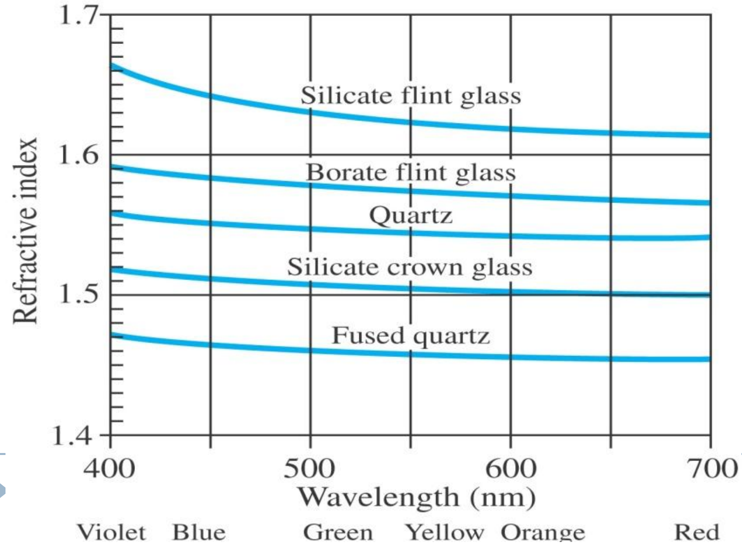


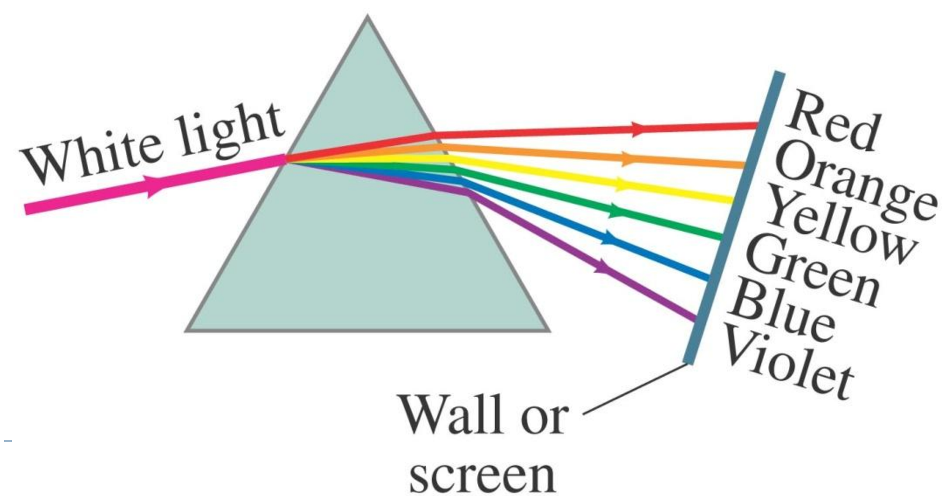
Visible Spectrum and Dispersion

The visible spectrum contains the full range of wavelengths of light that are visible to the human eye.



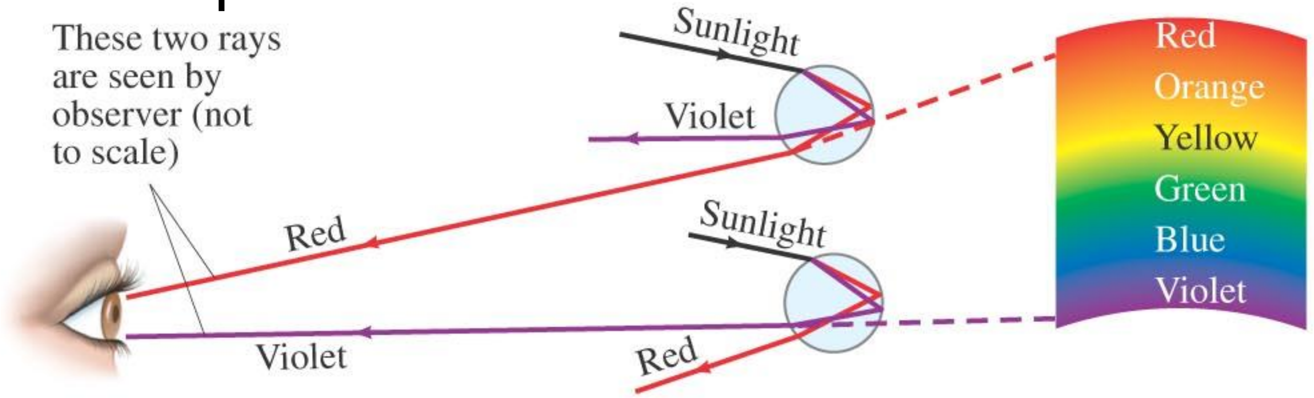
The index of refraction of many transparent materials, such as glass and water, varies slightly with wavelength. This is how prisms and water droplets create rainbows from sunlight.





Visible Spectrum and Dispersion

This spreading of light into the full spectrum is called dispersion.



Conceptual Example : Observed color of light under water.

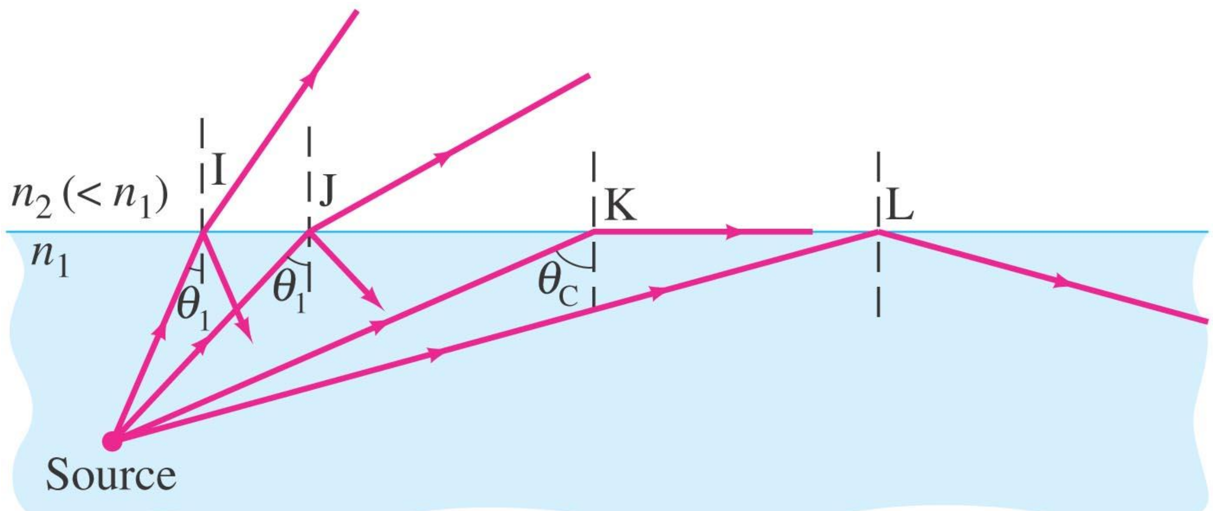
We said that color depends on wavelength. For example, for an object emitting 650 nm light in air, we see red. But this is true only in air. If we observe this same object when under water, it still looks red. But the wavelength in water λ_n is 650 nm/1.33 = 489 nm. Light with wavelength 489 nm would appear blue in air. Can you explain why the light appears red rather than blue when observed under water?

Total Internal Reflection; Fiber Optics

If light passes into a medium with a smaller index of refraction, the angle of refraction is larger. There is an angle of incidence for which the angle of refraction will be 90 ; this is called the critical angle:

$$\sin\theta_C = \frac{n_2}{n_1}\sin 90° = \frac{n_2}{n_1}.$$

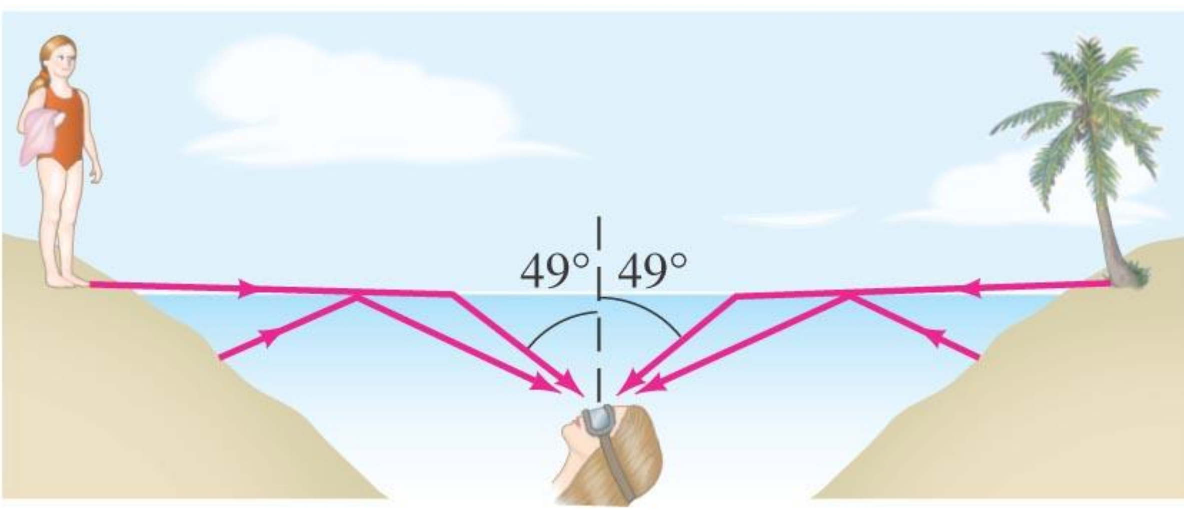
If the angle of incidence is larger than this, no transmission occurs. This is called total internal reflection.



Total Internal Reflection; Fiber Optics

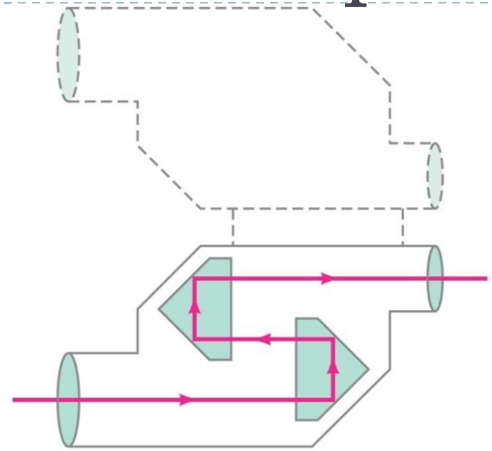
Conceptual Example: View up from under water.

Describe what a person would see who looked up at the world from beneath the perfectly smooth surface of a lake or swimming pool.

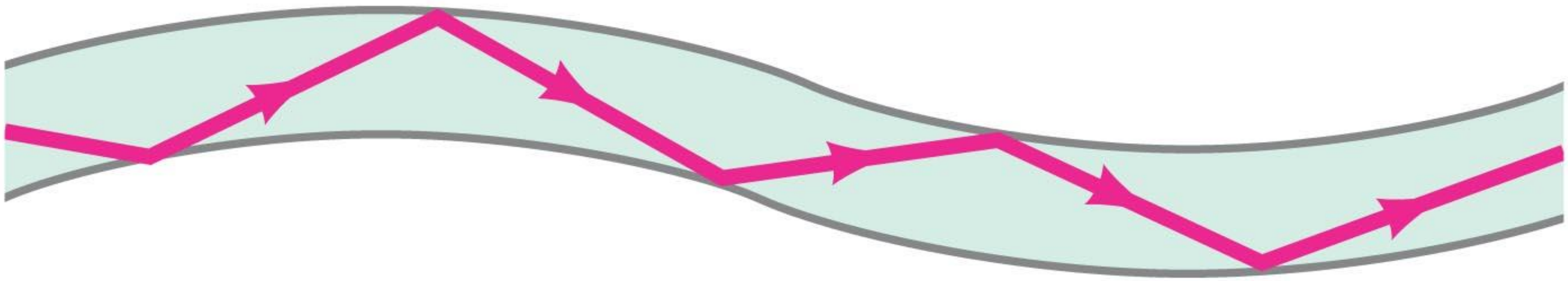


Total Internal Reflection; Fiber Optics

Binoculars often use total internal reflection; this gives true 100% reflection, which even the best mirror cannot do.



Optical fibers also depend on total internal reflection; they are therefore able to transmit light signals with very small losses.

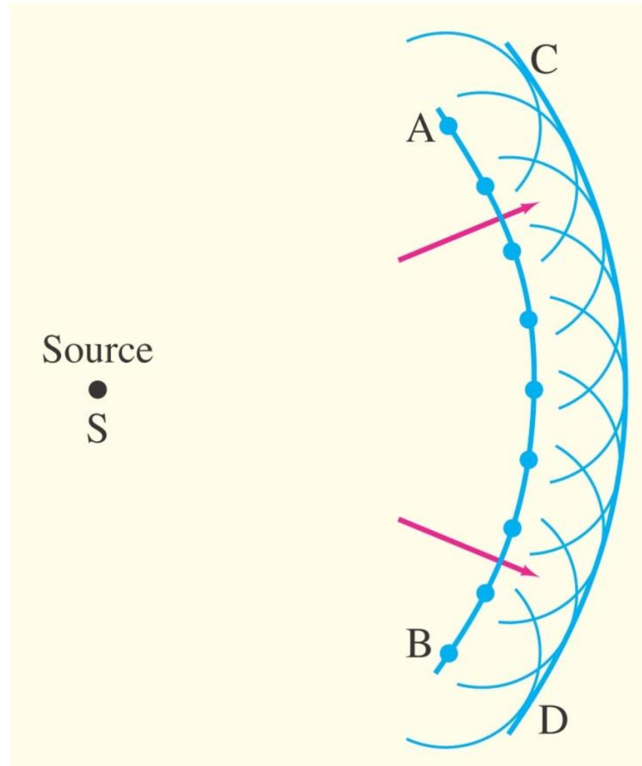


The Wave Nature of Light; Interference

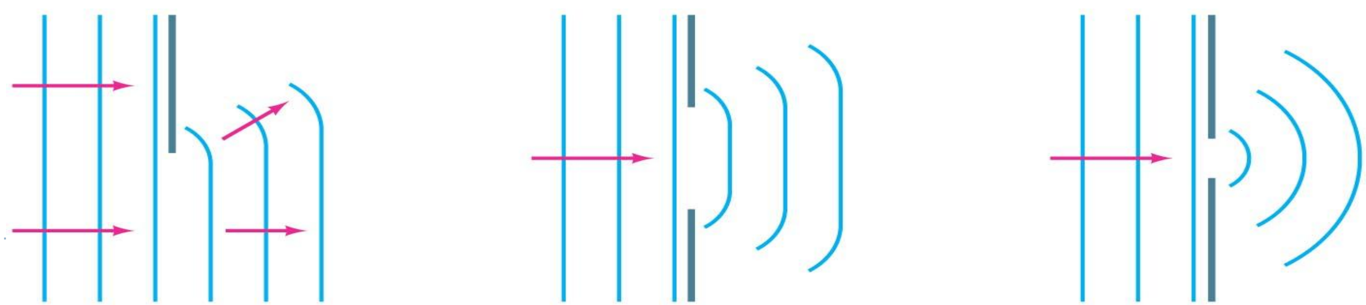
Waves versus Particles;

Huygens' Principle and DiffractionHuygens' principle:

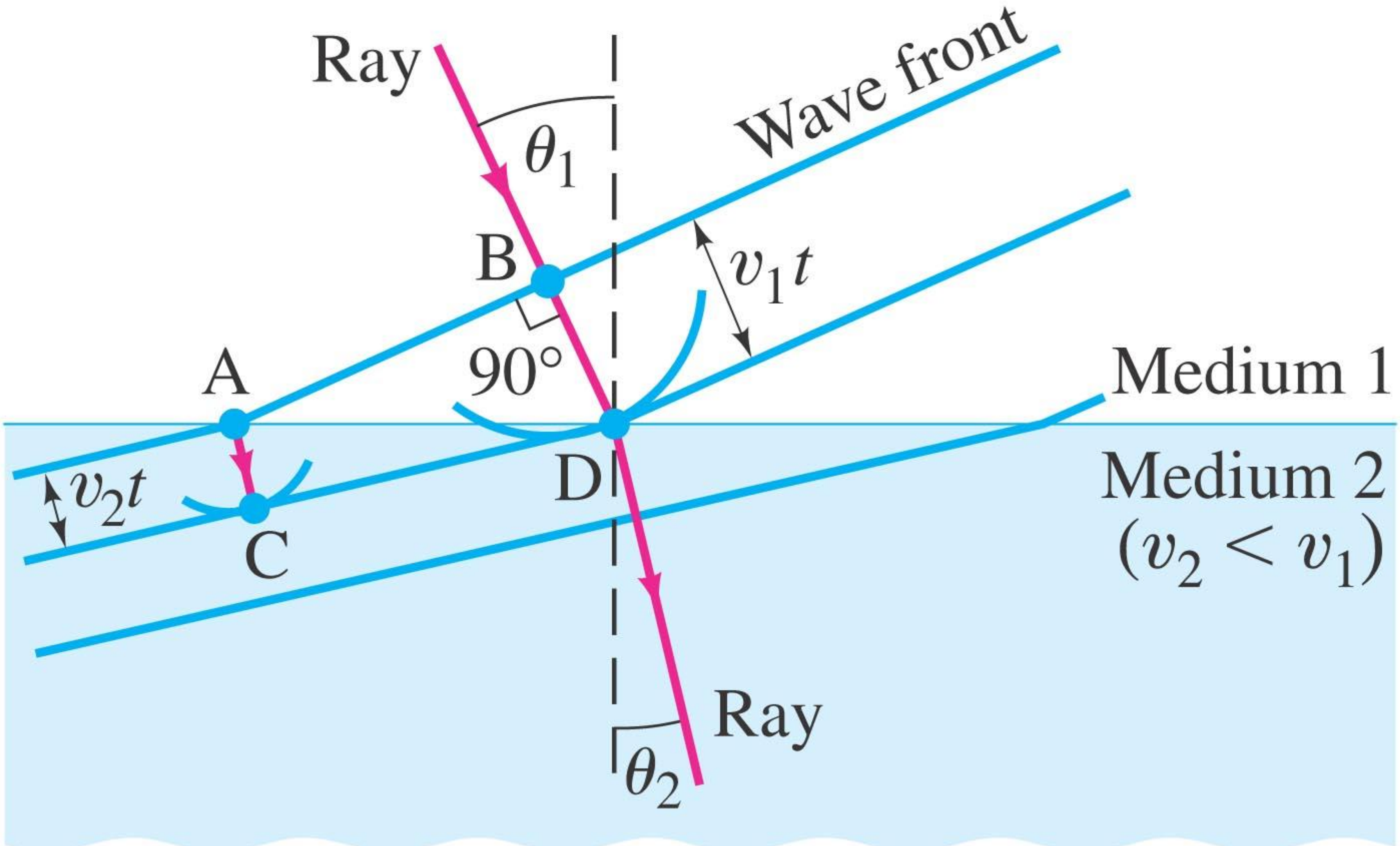
every point on a wave front acts as a point source; the wave front as it develops is tangent to all the wavelets.



Huygens' principle is consistent with diffraction:



Huygens' Principle and the Law of Refraction



Huygens' Principle and the Law of Refraction

Huygens' principle can also explain the law of refraction.

As the wavelets propagate from each point, they propagate more slowly in the medium of higher index of refraction.

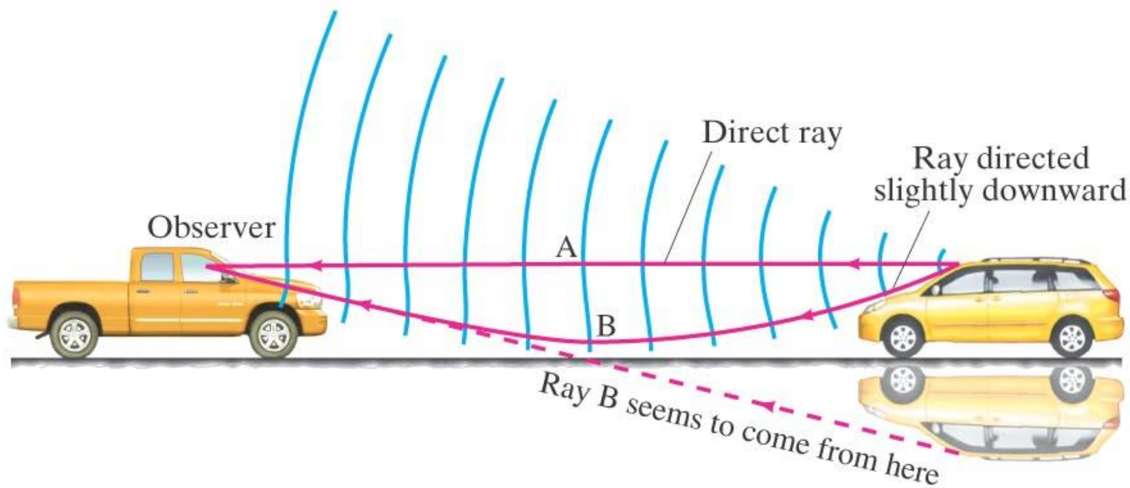
This leads to a bend in the wave front and therefore in the ray.

The frequency of the light does not change, but the wavelength does as it travels into a new medium:

$$\frac{\lambda_2}{\lambda_1} = \frac{v_2 t}{v_1 t} = \frac{v_2}{v_1} = \frac{n_1}{n_2}. \qquad \lambda_n = \frac{\lambda}{n}.$$

Huygens' Principle and the Law of Refraction

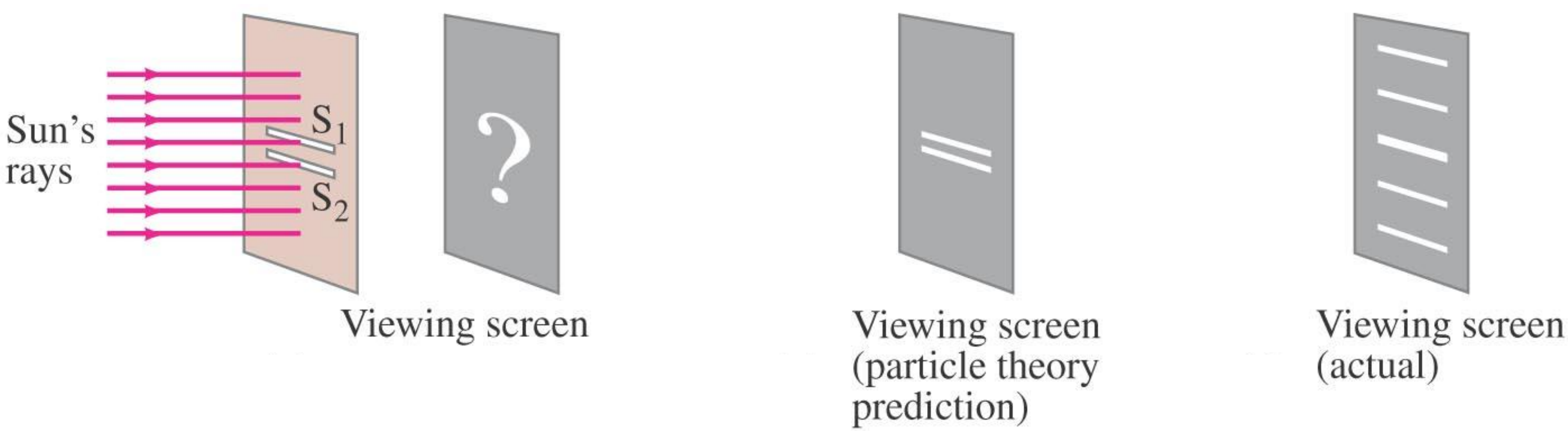
Highway mirages are due to a gradually changing index of refraction in heated air.



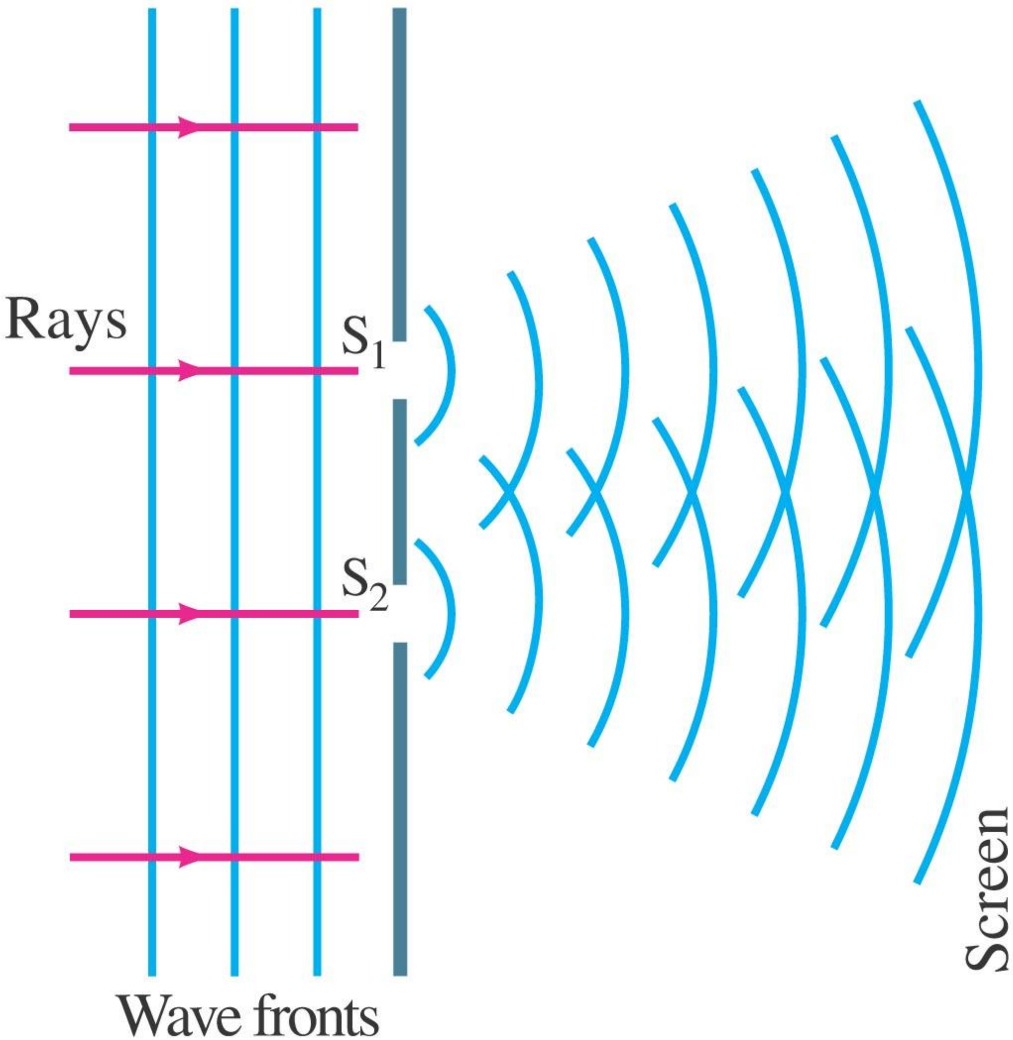
Interference – Young's Double-Slit Experiment

If light is a wave, interference effects will be seen, where one part of a wave front can interact with another part.

One way to study this is to do a double-slit experiment:



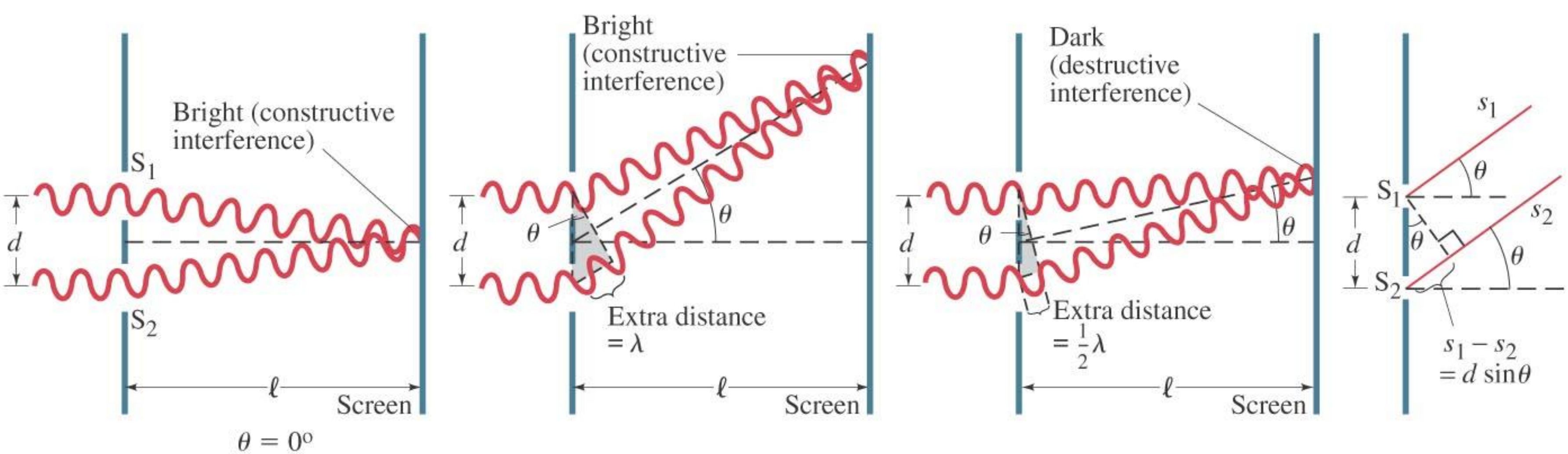
Interference – Young's Double-Slit Experiment



If light is a wave, there should be an interference pattern.

Interference – Young's Double-Slit Experiment

The interference occurs because each point on the screen is not the same distance from both slits. Depending on the path length difference, the wave can interfere constructively (bright spot) or destructively (dark spot).



Interference – Young's Double-Slit Experiment

We can use geometry to find the conditions for constructive and destructive interference:

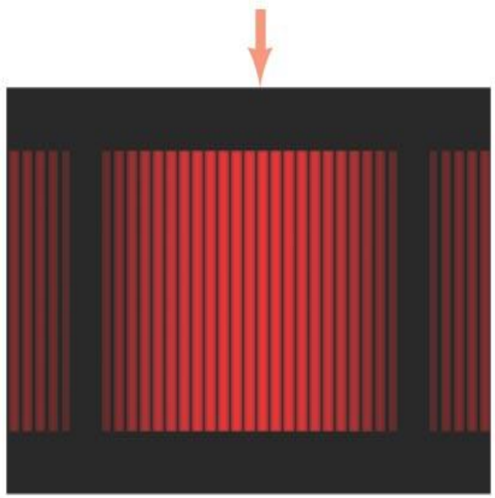
$$d \sin\theta = m\lambda, \qquad m = 0, 1, 2, \cdots. \qquad \begin{bmatrix} \text{constructive} \\ \text{interference} \\ \text{(bright)} \end{bmatrix}$$

and

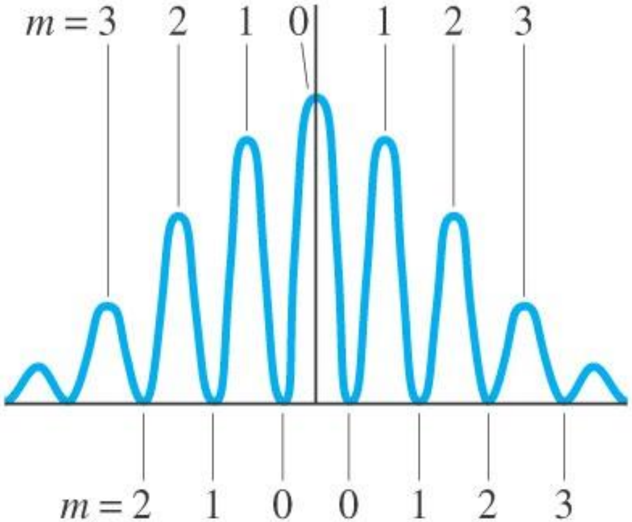
$$d \sin\theta = (m + \tfrac{1}{2})\lambda, \qquad m = 0, 1, 2, \cdots. \qquad \begin{bmatrix} \text{destructive} \\ \text{interference} \\ \text{(dark)} \end{bmatrix}$$

Interference – Young's Double-Slit Experiment

Between the maxima and the minima, the interference varies smoothly.



Constructive interference



Destructive interference

Conceptual Example : Interference pattern lines.

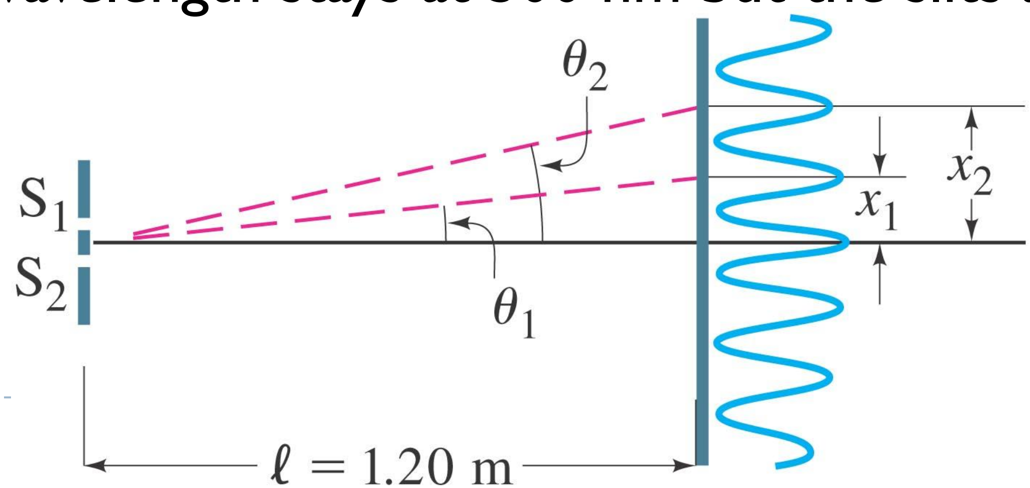
(a) Will there be an infinite number of points on the viewing screen where constructive and destructive interference occur, or only a finite number of points? (b) Are neighboring points of constructive interference uniformly spaced, or is the spacing between neighboring points of constructive interference not uniform?

Interference – Young's Double-Slit Experiment

Example : Line spacing for double-slit interference.

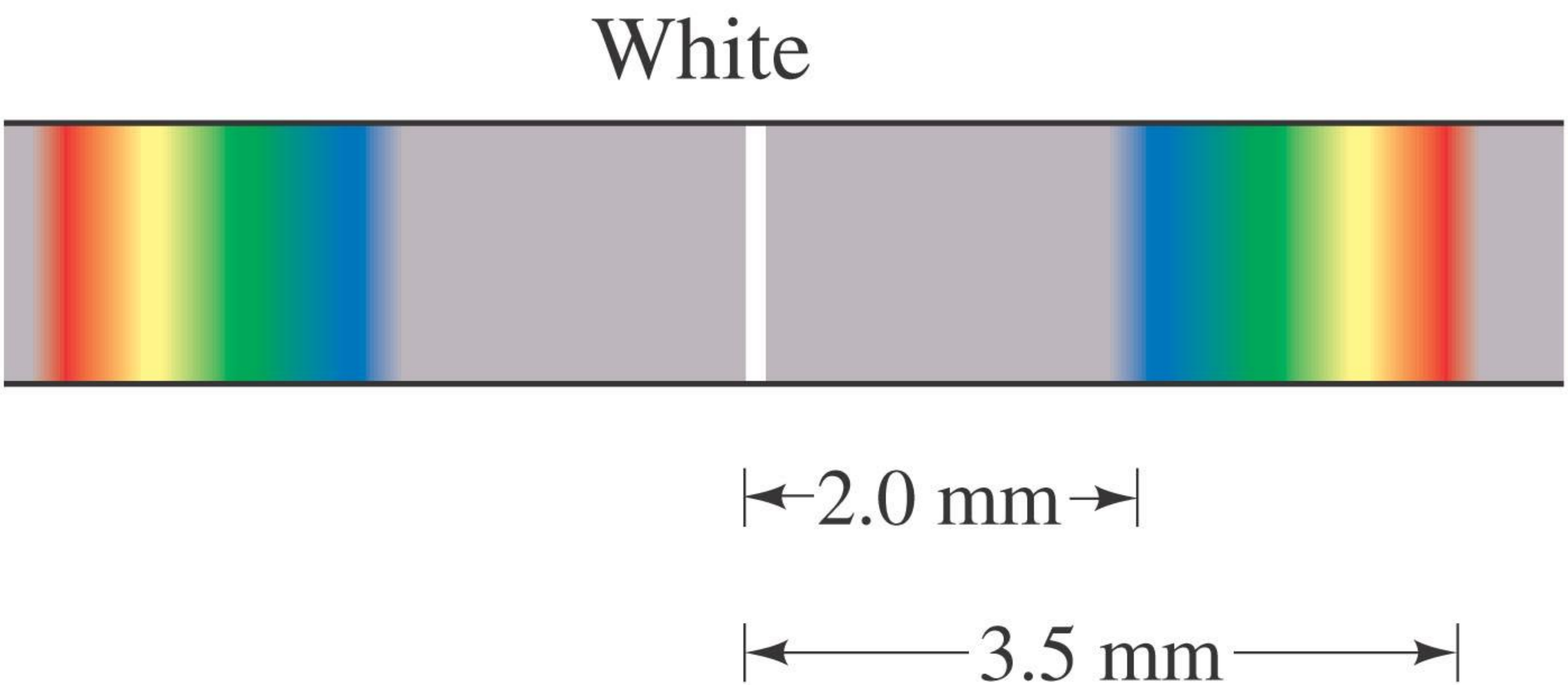
A screen containing two slits 0.100 mm apart is 1.20 m from the viewing screen. Light of wavelength λ = 500 nm falls on the slits from a distant source. Approximately how far apart will adjacent bright interference fringes be on the screen?

(a) What happens to the interference pattern if the incident light (500 nm) is replaced by light of wavelength 700 nm? (b) What happens instead if the wavelength stays at 500 nm but the slits are moved farther apart?



Interference – Young's Double-Slit Experiment

Since the position of the maxima (except the central one) depends on wavelength, the first- and higher-order fringes contain a spectrum of colors.

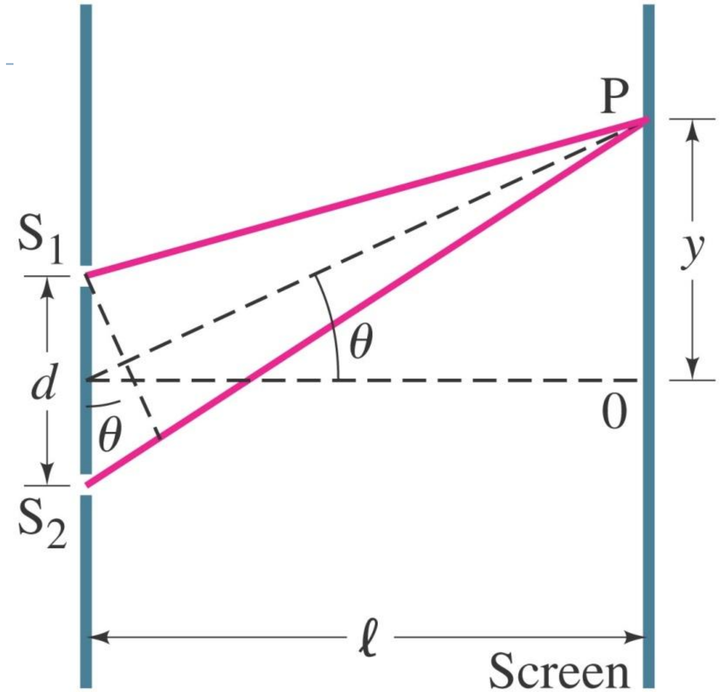


Interference – Young's Double-Slit Experiment

Example : Wavelengths from double-slit interference.

White light passes through two slits 0.50 mm apart, and an interference pattern is observed on a screen 2.5 m away. The first-order fringe resembles a rainbow with violet and red light at opposite ends. The violet light is about 2.0 mm and the red 3.5 mm from the center of the central white fringe. Estimate the wavelengths for the violet and red light.

Intensity in the Double-Slit Interference Pattern

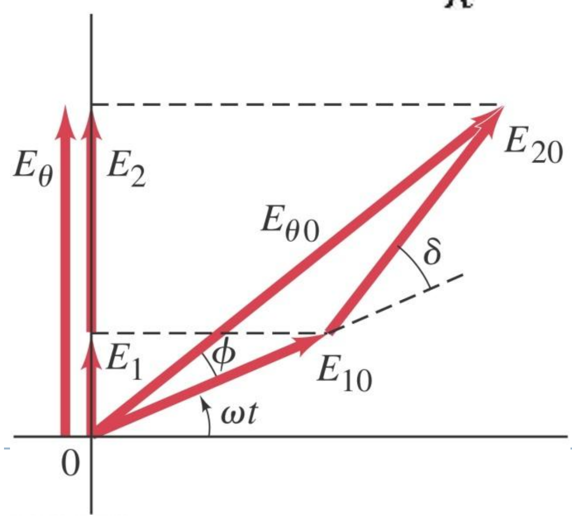


The electric fields at the point P from the two slits are given by

$$E_1 = E_{10} \sin \omega t$$
$$E_2 = E_{20} \sin(\omega t + \delta)$$

where

$$\delta = \frac{2\pi}{\lambda} d \sin \theta.$$



The two waves can be added using phasors, to take the phase difference into account:

$$E_\theta = 2E_0 \cos\frac{\delta}{2} \sin\left(\omega t + \frac{\delta}{2}\right).$$

Intensity in the Double-Slit Interference Pattern

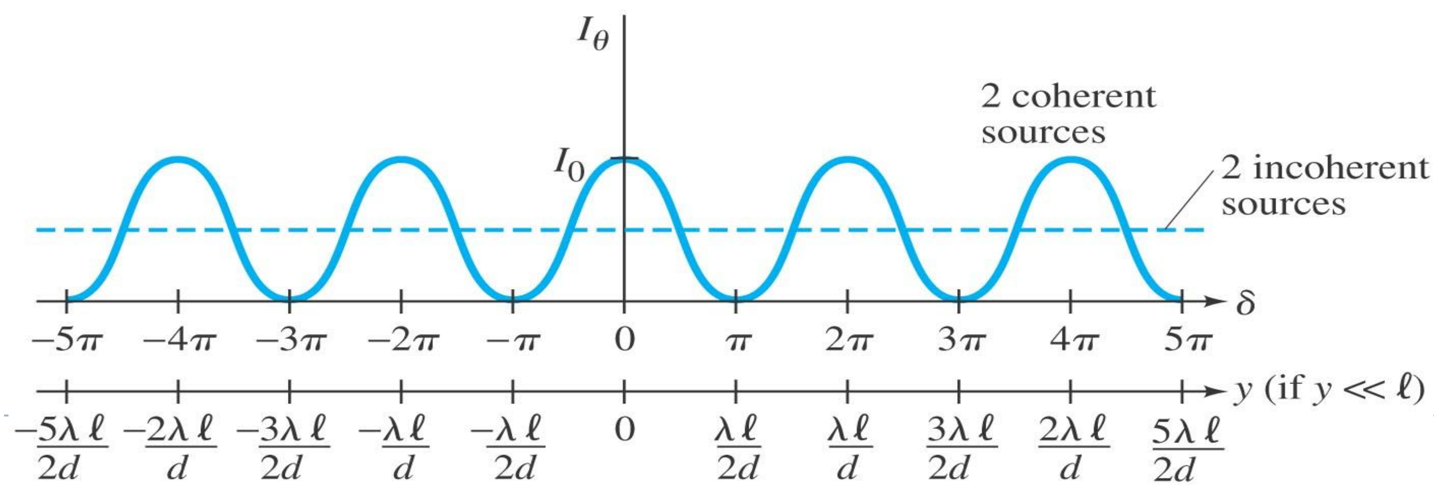
The time-averaged intensity is proportional to the square of the field:

$$I_\theta = I_0 \cos^2 \frac{\delta}{2}$$

$$= I_0 \cos^2\left(\frac{\pi d \sin\theta}{\lambda}\right)$$

$$I_\theta = I_0\left[\cos\left(\frac{\pi d}{\lambda \ell} y\right)\right]^2. \qquad [y \ll \ell,\ d \ll \ell]$$

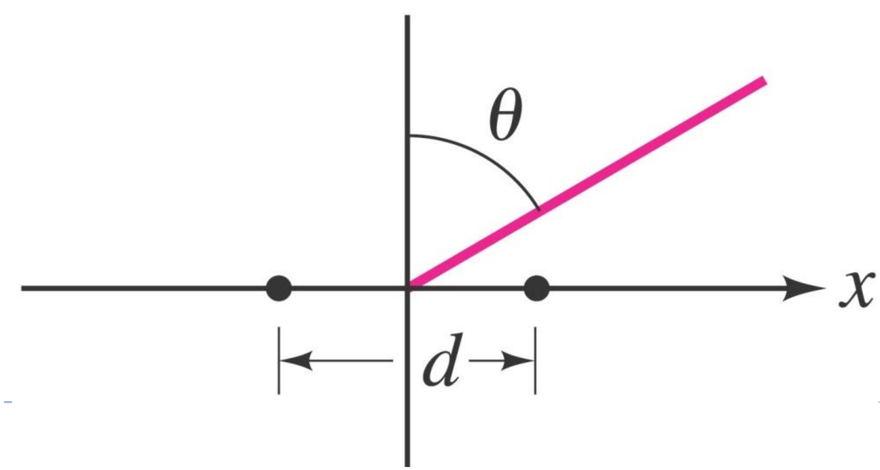
This plot shows the intensity as a function of angle.



Intensity in the Double-Slit Interference Pattern

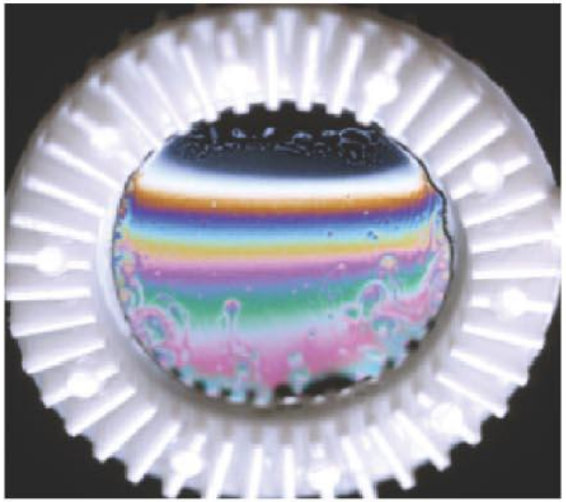
Example :Antenna intensity.

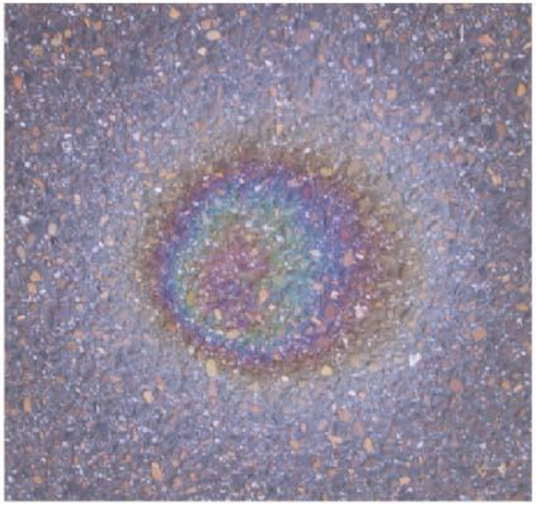
Two radio antennas are located close to each other, separated by a distance d. The antennas radiate in phase with each other, emitting waves of intensity I_0 at wavelength λ. (a) Calculate the net intensity as a function of ϑ for points very far from the antennas. (b) For $d = \lambda$, determine I and find in which directions I is a maximum and a minimum. (c) Repeat part (b) when $d = \lambda/2$.



Interference in Thin Films

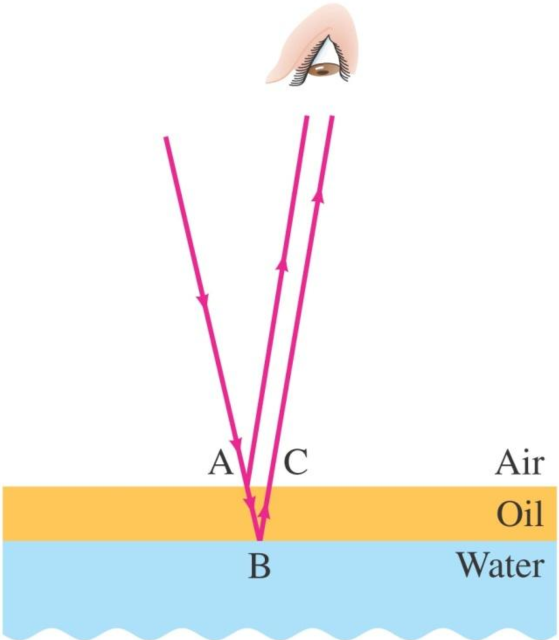
Another way path lengths can differ, and waves interfere, is if they travel through different media. If there is a very thin film of material – a few wavelengths thick – light will reflect from both the bottom and the top of the layer, causing interference. This can be seen in soap bubbles and oil slicks.



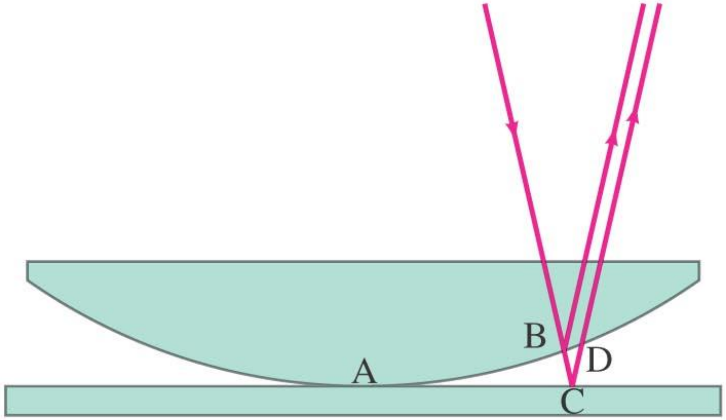


Interference in Thin Films

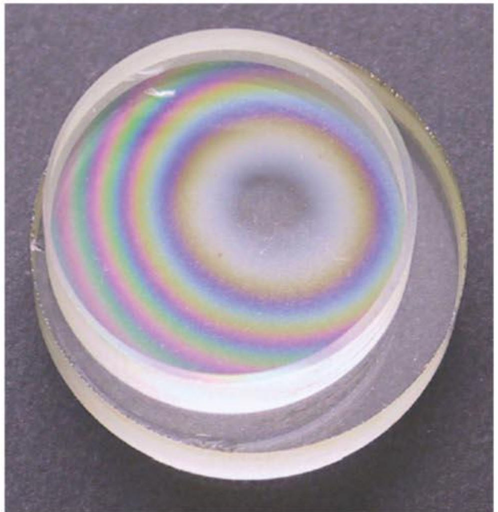
The wavelength of the light will be different in the oil and the air, and the reflections at points A and B may or may not involve phase changes.



A similar effect takes place when a shallowly curved piece of glass is placed on a flat one. When viewed from above, concentric circles appear that are called Newton's rings.



(a)



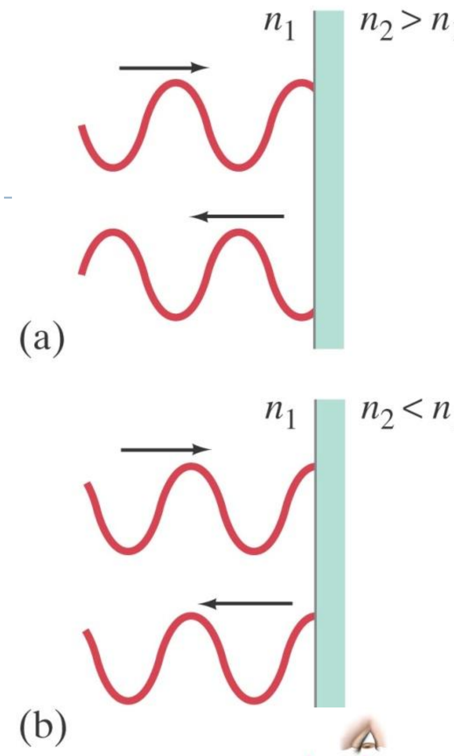
(b)

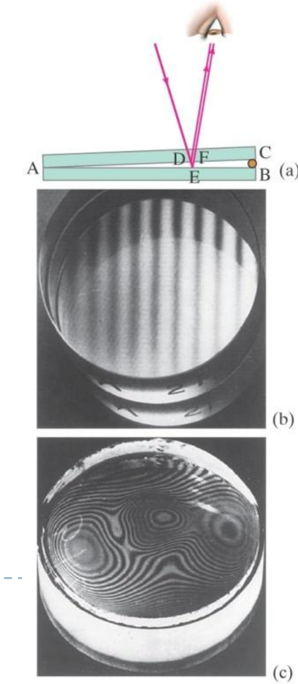
Interference in Thin Films

A beam of light reflected by a material with index of refraction greater than that of the material in which it is traveling, changes phase by 180° or ½ cycle.

Example : Thin film of air, wedge-shaped.

A very fine wire 7.35 x 10^{-3} mm in diameter is placed between two flat glass plates. Light whose wavelength in air is 600 nm falls (and is viewed) perpendicular to the plates and a series of bright and dark bands is seen. How many light and dark bands will there be in this case? Will the area next to the wire be bright or dark?

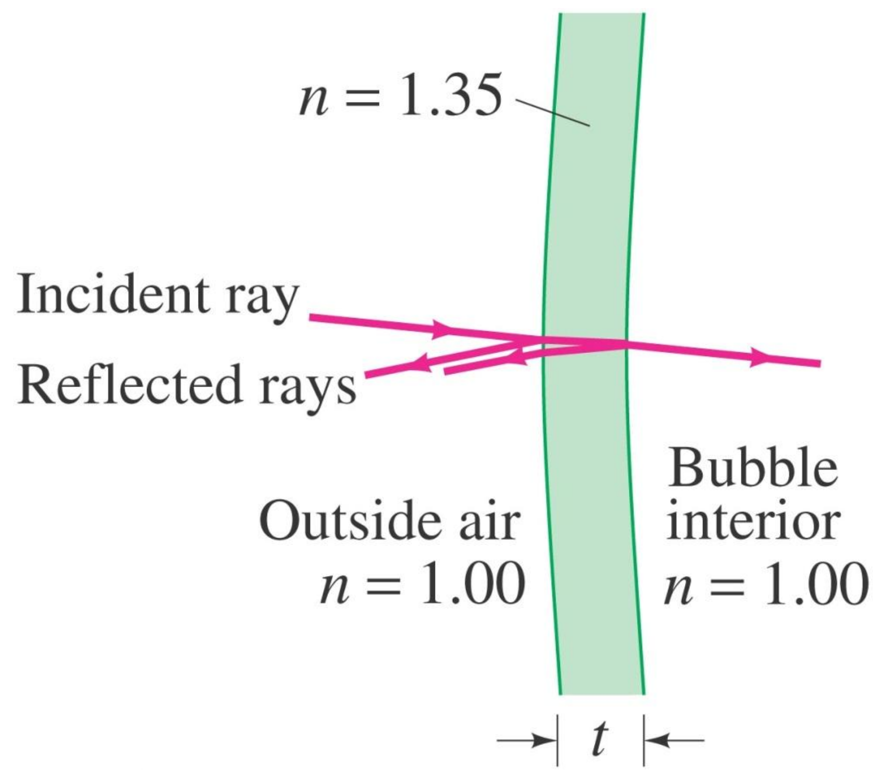




Interference in Thin Films

Example : Thickness of soap bubble skin.

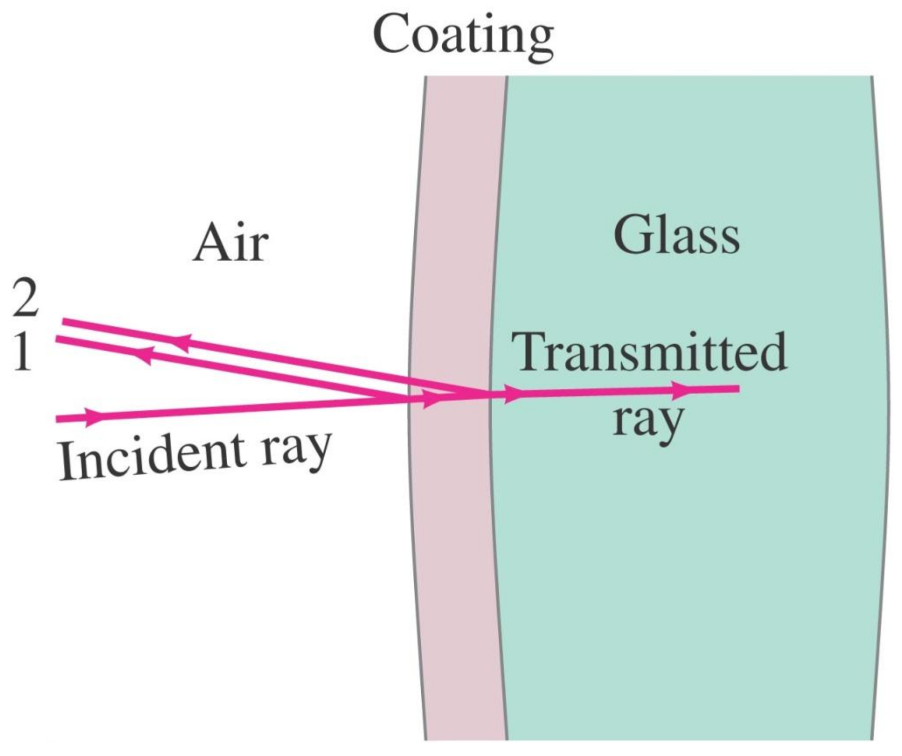
A soap bubble appears green (λ = 540 nm) at the point on its front surface nearest the viewer. What is the smallest thickness the soap bubble film could have? Assume n = 1.35.



Interference in Thin Films

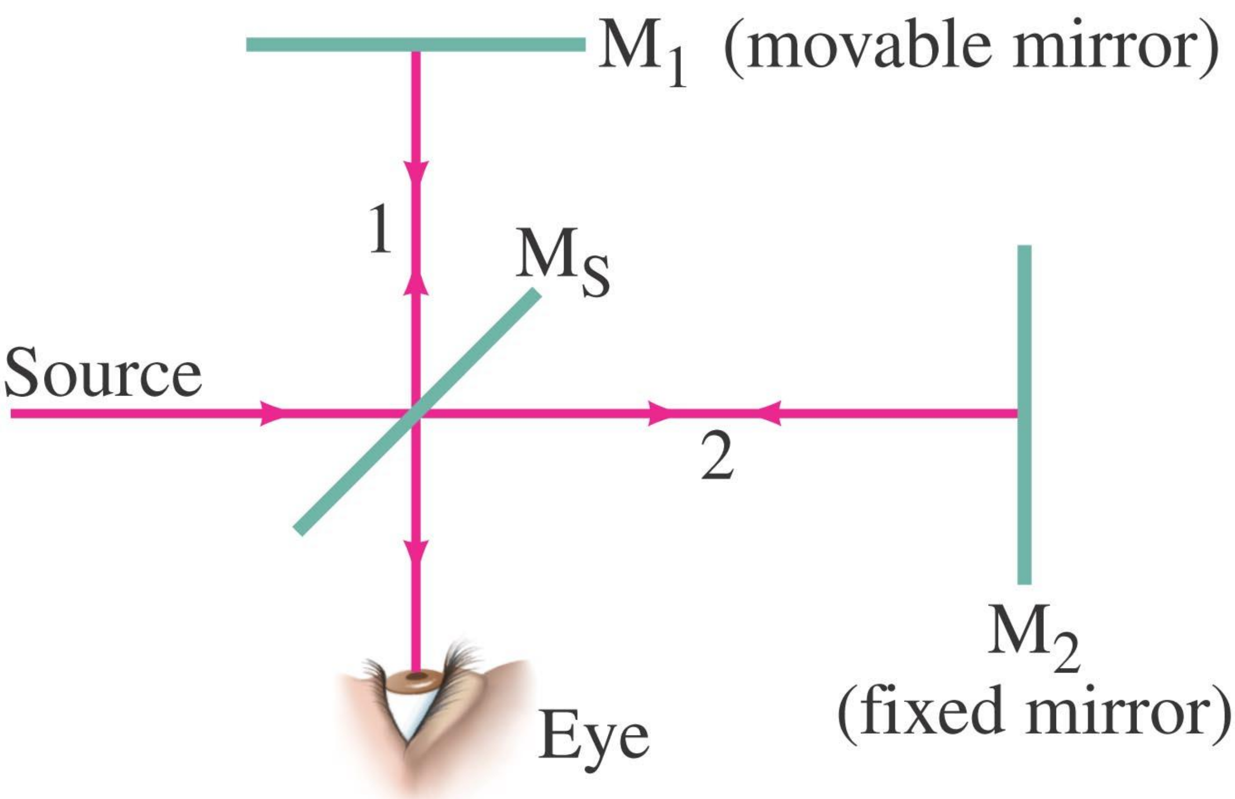
Example : Nonreflective coating.

What is the thickness of an optical coating of MgF_2 whose index of refraction is n = 1.38 and which is designed to eliminate reflected light at wavelengths (in air) around 550 nm when incident normally on glass for which n = 1.50?



Michelson Interferometer

The Michelson interferometer is centered around a beam splitter, which transmits about half the light hitting it and reflects the rest. It can be a very sensitive measure of length.



Luminous Intensity

The intensity of light as perceived depends not only on the actual intensity but also on the sensitivity of the eye at different wavelengths.

Luminous flux: 1 lumen = 1/683 W of 555-nm light

Luminous intensity: 1 candela = 1 lumen/steradian

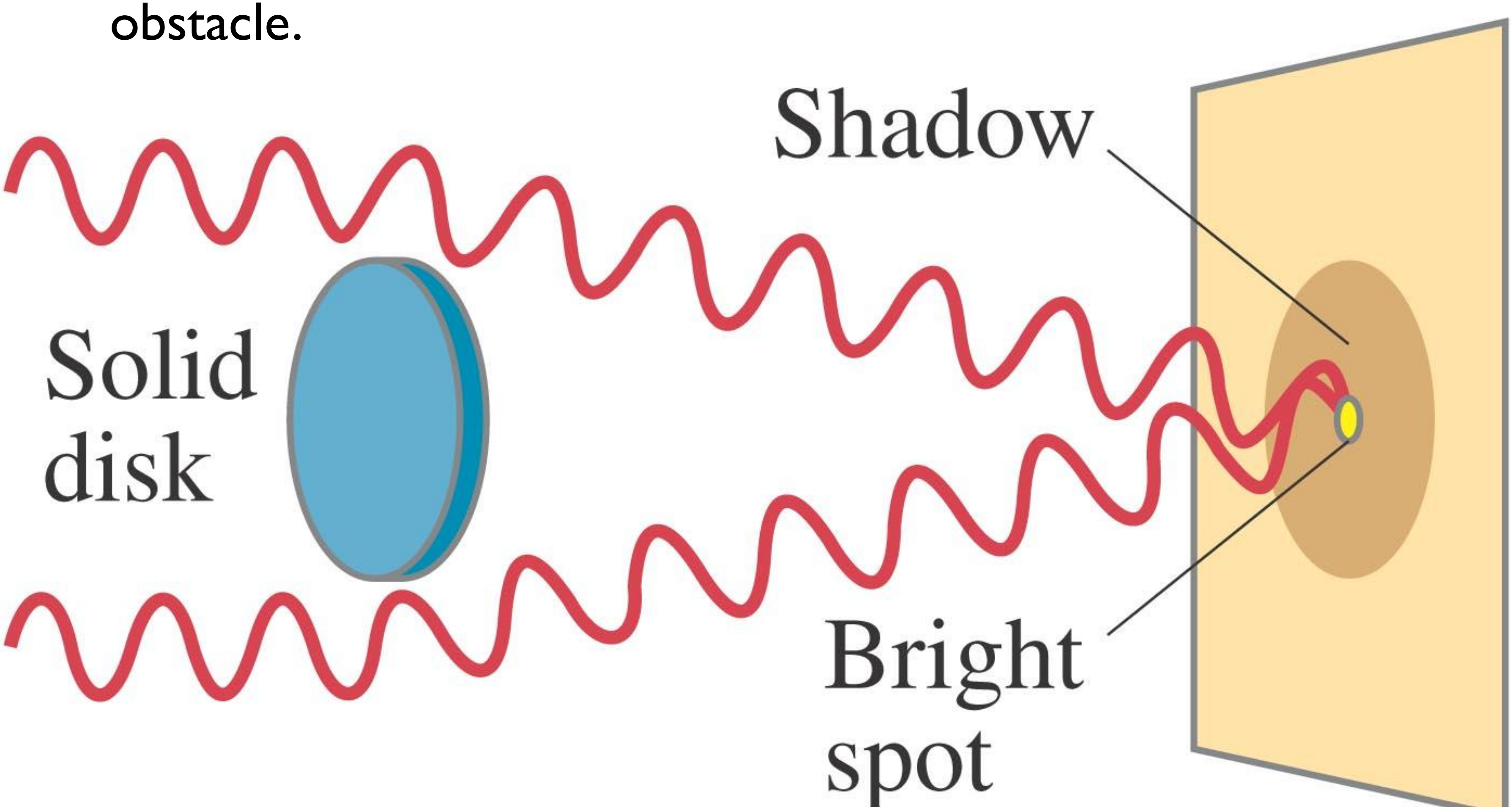
Illuminance: luminous flux per unit area

Example : Lightbulb illuminance.

The brightness of a particular type of 100-W lightbulb is rated at 1700 lm. Determine (a) the luminous intensity and (b) the illuminance at a distance of 2.0 m.

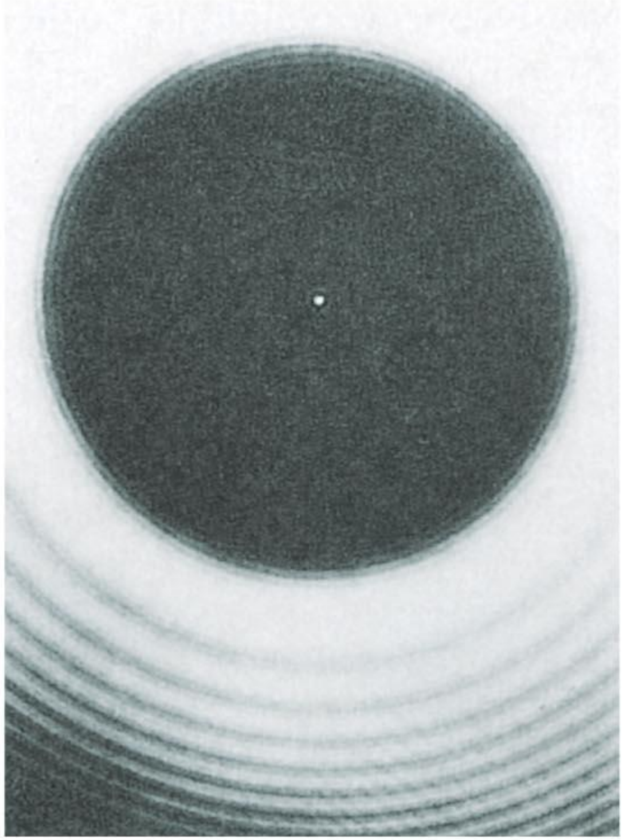
Diffraction by a Single Slit or Disk

If light is a wave, it will diffract around a single slit or obstacle.



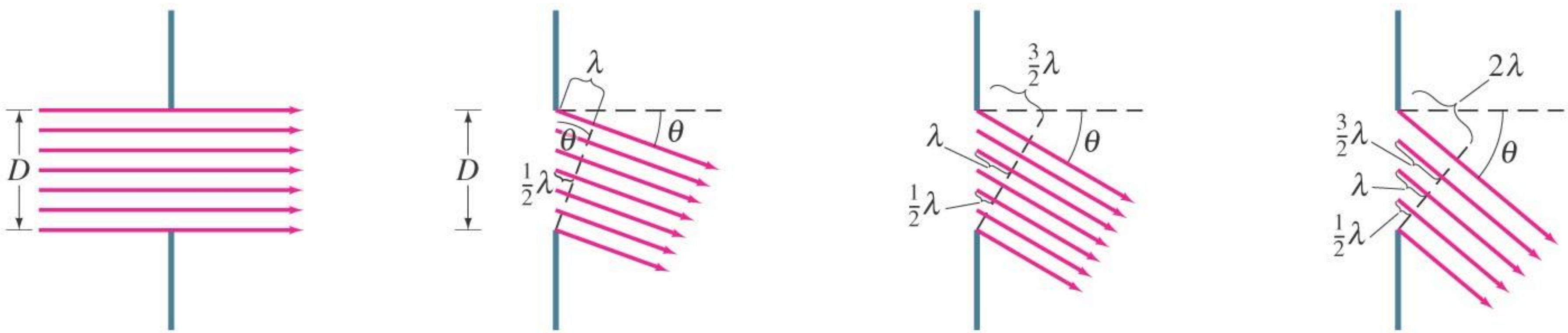
Diffraction by a Single Slit or Disk

The resulting pattern of light and dark stripes is called a diffraction pattern.



Diffraction by a Single Slit or Disk

This pattern arises because different points along a slit create wavelets that interfere with each other just as a double slit would.



$\theta = 0$
Bright

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

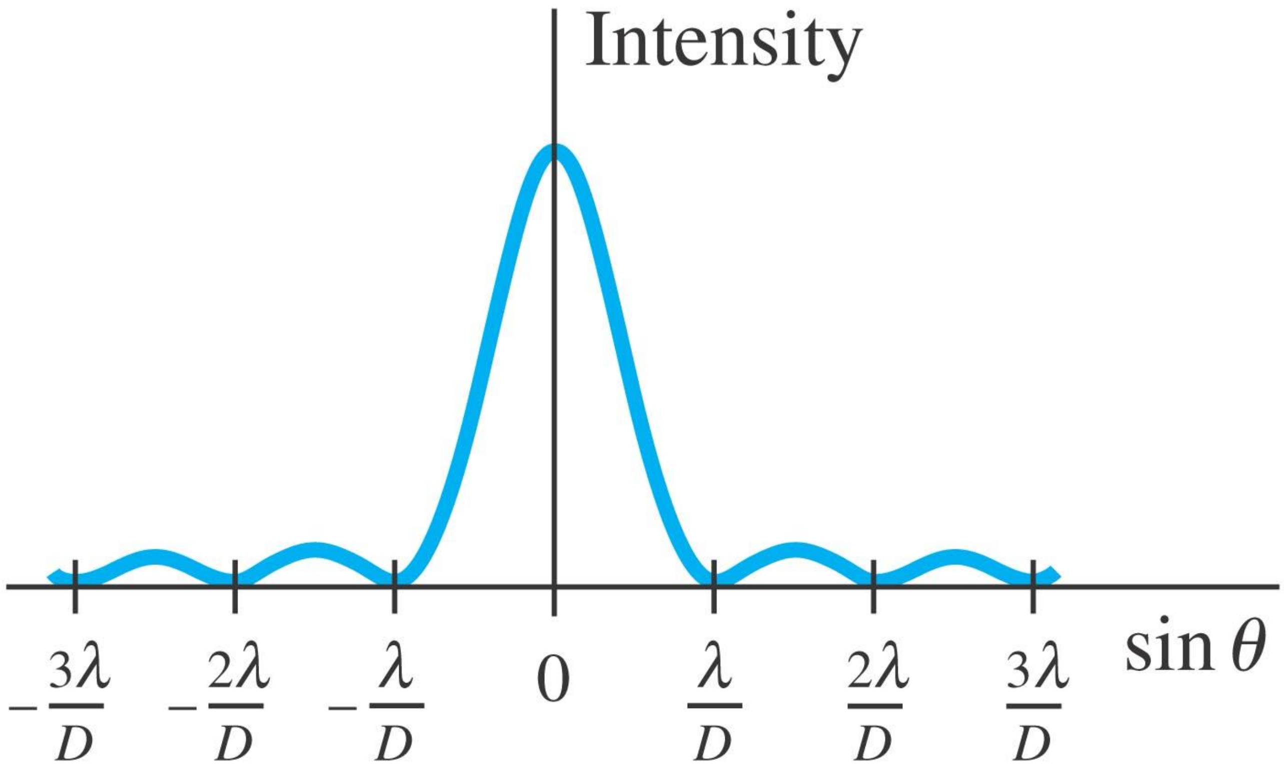
$\sin\theta = \frac{3\lambda}{2D}$
Bright

$\sin\theta = \frac{2\lambda}{D}$
Dark

Diffraction by a Single Slit or Disk

The minima of the single-slit diffraction pattern occur when

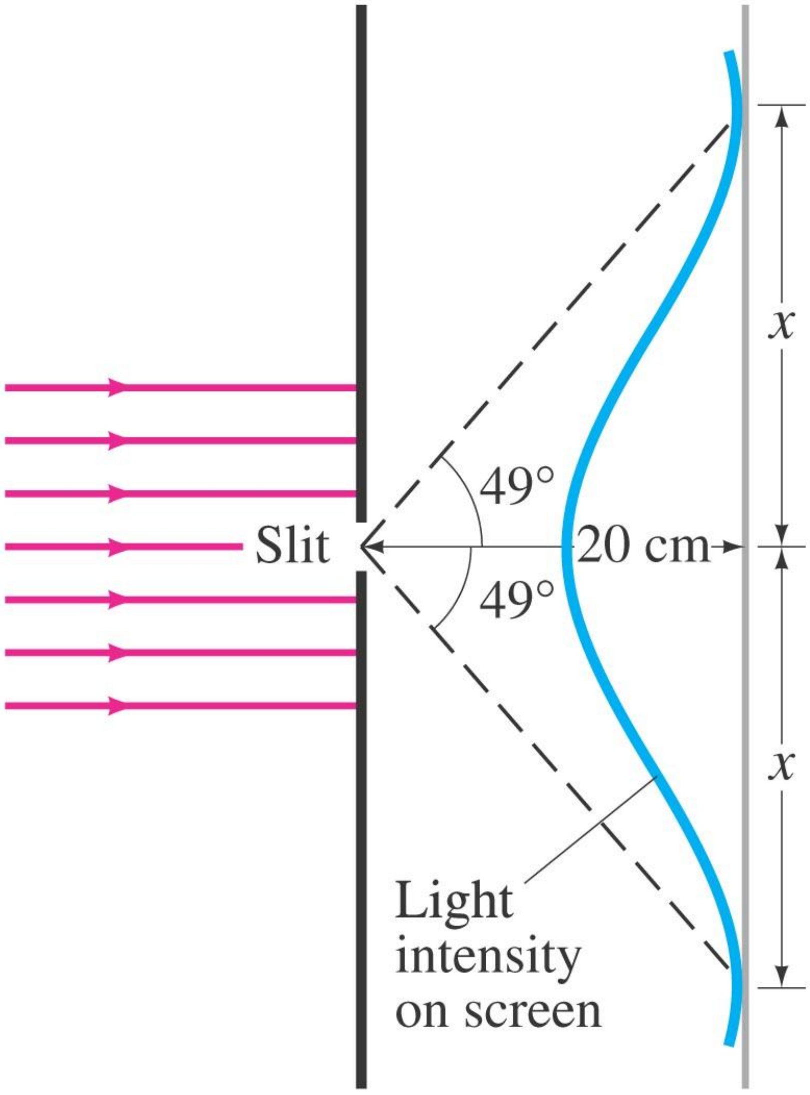
$$D\sin\theta = m\lambda, \qquad m = \pm 1, \pm 2, \pm 3, \cdots. \qquad \text{[minima]}$$



Diffraction by a Single Slit or Disk

Example : Single-slit diffraction maximum.

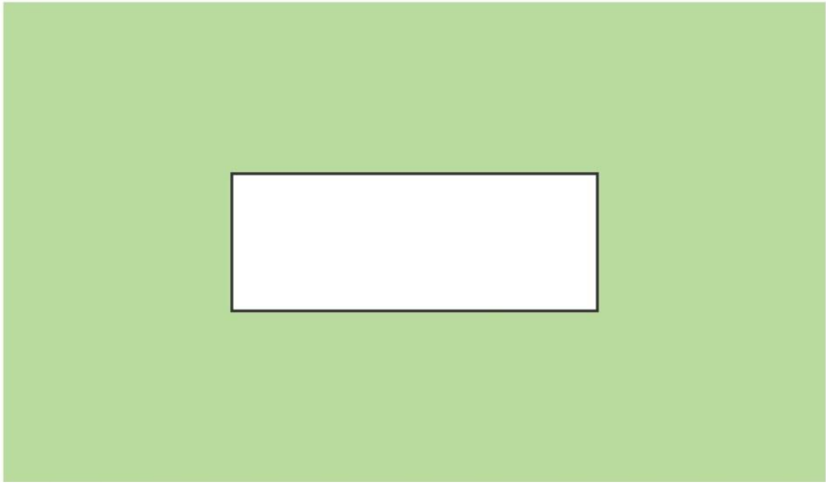
Light of wavelength 750 nm passes through a slit 1.0×10^{-3} mm wide. How wide is the central maximum (a) in degrees, and (b) in centimeters, on a screen 20 cm away?



Diffraction by a Single Slit or Disk

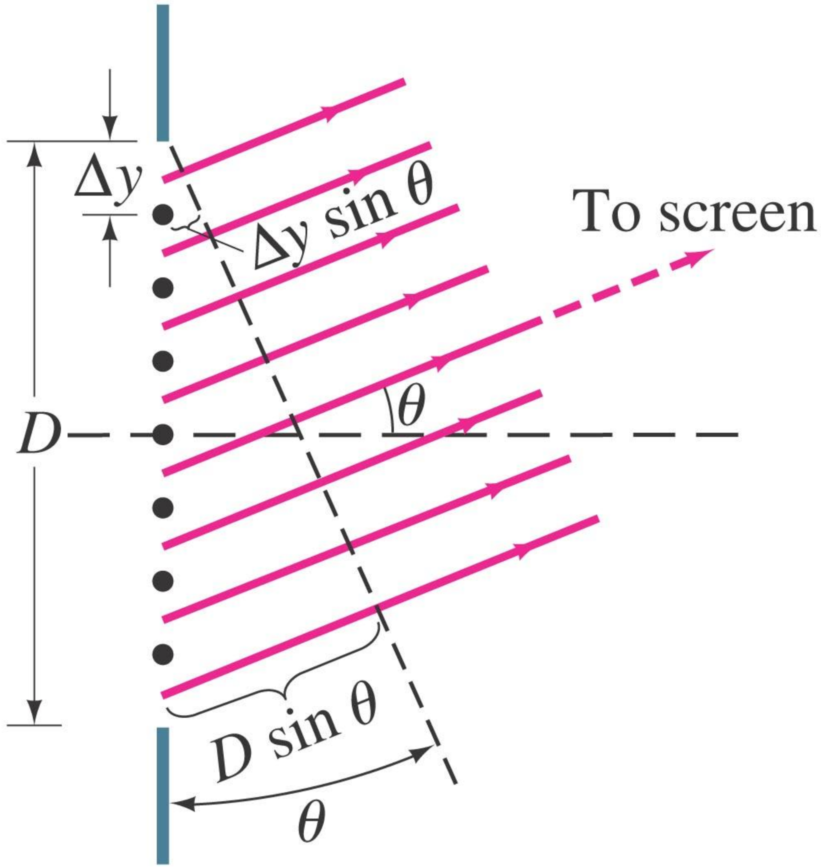
Conceptual Example Diffraction spreads.

Light shines through a rectangular hole that is narrower in the vertical direction than the horizontal. (a) Would you expect the diffraction pattern to be more spread out in the vertical direction or in the horizontal direction? (b) Should a rectangular loudspeaker horn at a stadium be high and narrow, or wide and flat?



Intensity in Single-Slit Diffraction Pattern

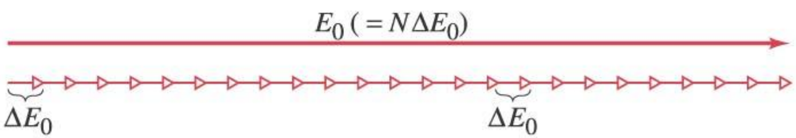
Light passing through a single slit can be divided into a series of narrower strips; each contributes the same amplitude to the total intensity on the screen, but the phases differ due to the differing path lengths:



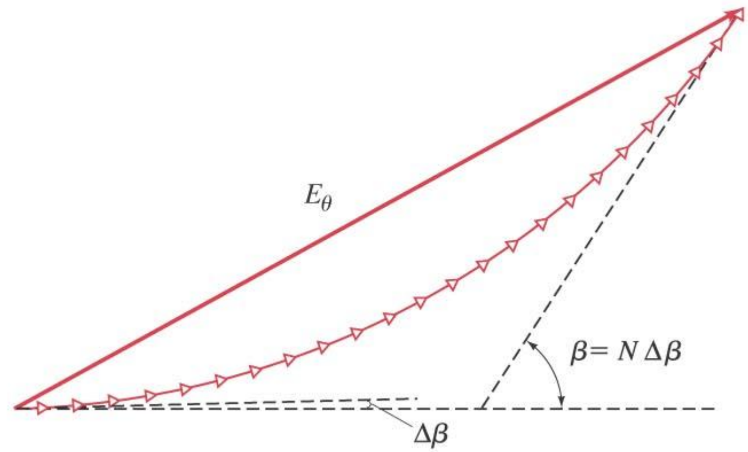
$$\Delta\beta = \frac{2\pi}{\lambda}\Delta y \sin\theta.$$

Intensity in Single-Slit Diffraction Pattern

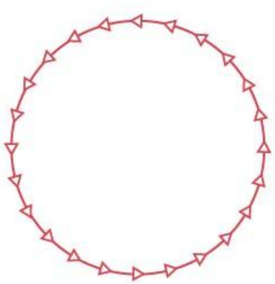
Phasor diagrams give us the intensity as a function of angle.



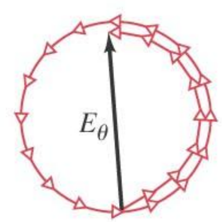
At center, $\theta = 0$.



Between center and first minimum.



First minimum, $E_\theta = 0$ ($\beta = 2\pi = 360°$).

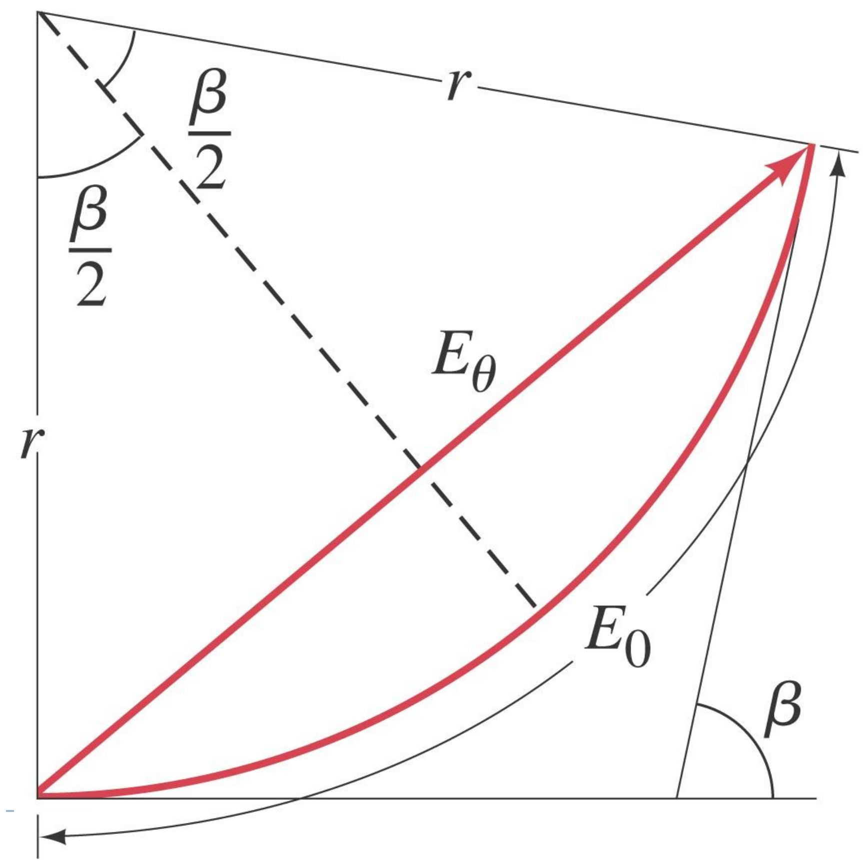


Near secondary maximum.

Intensity in Single-Slit Diffraction Pattern

Taking the limit as the width becomes infinitesimally small gives the field as a function of angle:

$$E_\theta = E_0 \frac{\sin \beta/2}{\beta/2}.$$



Finally, we have the phase difference and the intensity as a function of angle:

$$\beta = \frac{2\pi}{\lambda} D \sin\theta.$$

and

$$I_\theta = I_0 \left(\frac{\sin \beta/2}{\beta/2} \right)^2.$$

Intensity in Single-Slit Diffraction Pattern

Example : Intensity at secondary maxima.

Estimate the intensities of the first two secondary maxima to either side of the central maximum.

Diffraction in the Double-Slit Experiment

The double-slit experiment also exhibits diffraction effects, as the slits have a finite width. This means the amplitude at an angle ϑ will be modified by the same factor as in the single-slit experiment:

$$E_{\theta 0} = 2E_0\left(\frac{\sin\beta/2}{\beta/2}\right)\cos\frac{\delta}{2}.$$

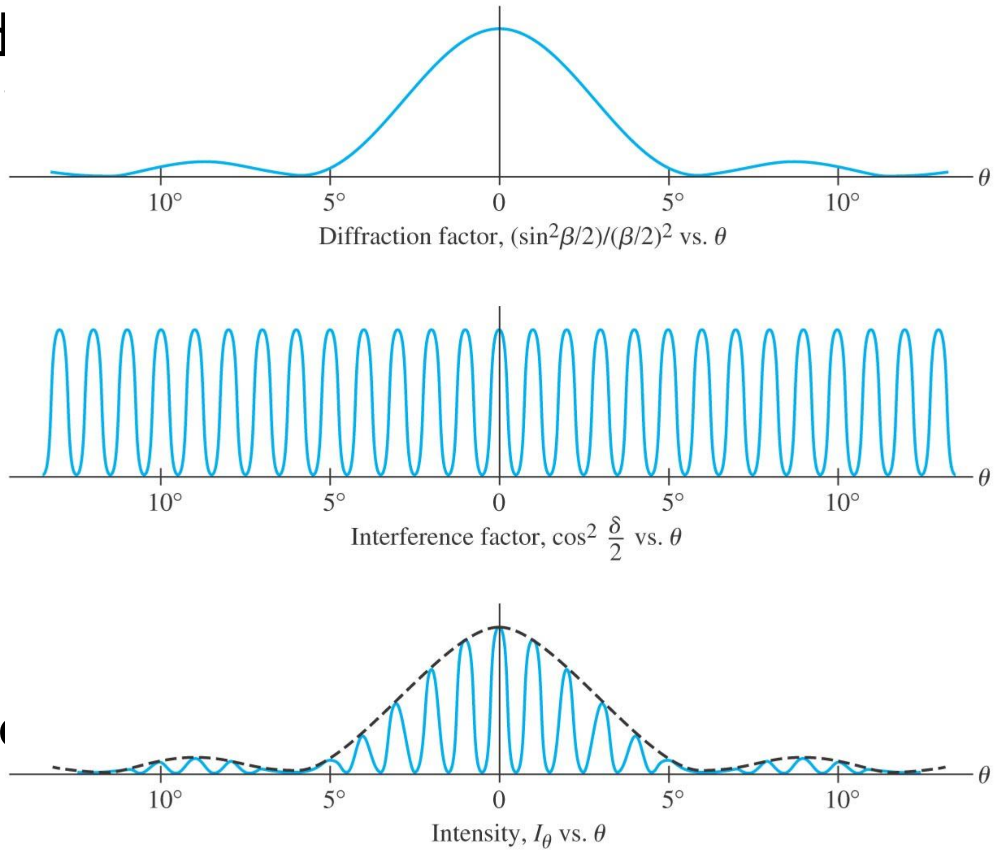
The intensity is, as usual, proportional to the square of the field.

Diffraction in the Double-Slit Experiment

The diffraction factor (depend on β) appears as an "envelope modifying the more rapidly varying interference factor (depends on δ).

Example : Diffraction plus interference.

Show why the central diffraction peak shown, plotted for the case where $d = 6D = 60\lambda$, contains 11 interference fringes.



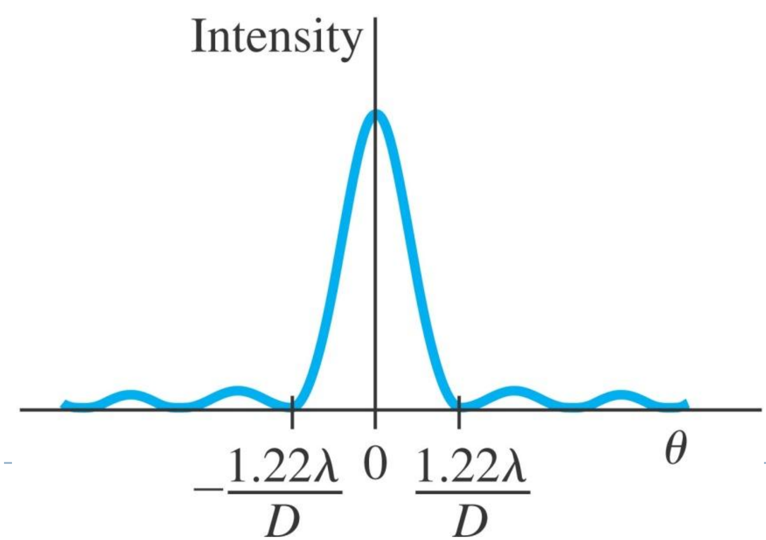
Limits of Resolution; Circular Apertures

Resolution is the distance at which a lens can barely distinguish two separate objects.

Resolution is limited by aberrations and by diffraction. Aberrations can be minimized, but diffraction is unavoidable; it is due to the size of the lens compared to the wavelength of the light.

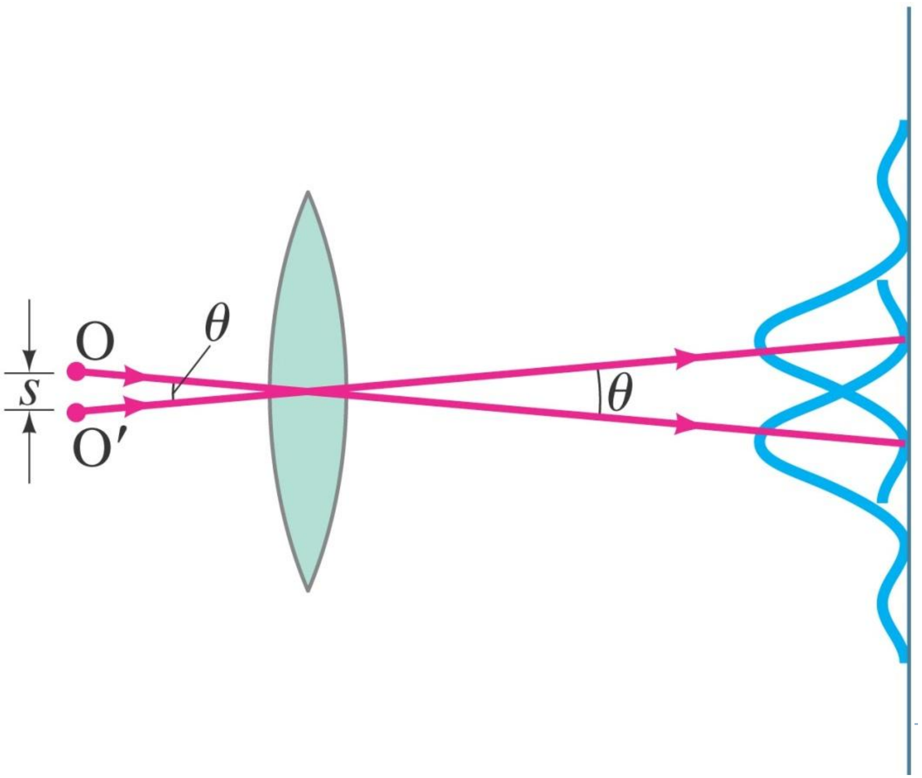
For a circular aperture of diameter *D*, the central maximum has an angular width:

$$\theta = \frac{1.22\lambda}{D}. \qquad [\theta \text{ in radians}]$$



Limits of Resolution; Circular Apertures

The Rayleigh criterion states that two images are just resolvable when the center of one peak is over the first minimum of the other.



Limits of Resolution; Circular Apertures

Example : Hubble Space Telescope.

The Hubble Space Telescope (HST) is a reflecting telescope that was placed in orbit above the Earth's atmosphere, so its resolution would not be limited by turbulence in the atmosphere. Its objective diameter is 2.4 m. For visible light, say λ = 550 nm, estimate the improvement in resolution the Hubble offers over Earth-bound telescopes, which are limited in resolution by movement of the Earth's atmosphere to about half an arc second. (Each degree is divided into 60 minutes each containing 60 seconds, so 1 = 3600 arc seconds.)

$$\theta = \frac{1}{2}\left(\frac{1}{3600}\right)^0 \left(\frac{2\pi rad}{360^0}\right) = 2.4*10^{-6} rad$$

$$\theta = \frac{1.22\lambda}{D} = \frac{1.22(550*10^{-9} m)}{2.4m} = 2.8*10^{-7} rad$$

Limits of Resolution; Circular Apertures

Example: Eye resolution.

You are in an airplane at an altitude of 10,000 m. If you look down at the ground, estimate the minimum separation s between objects that you could distinguish. Could you count cars in a parking lot? Consider only diffraction, and assume your pupil is about 3.0 mm in diameter and λ = 550 nm.

Hint: $s = l\theta$

Resolution of Telescopes and Microscopes; the λ Limit

For telescopes, the resolution limit is as we have defined it:

$$\theta = \frac{1.22\lambda}{D}. \qquad [\theta \text{ in radians}]$$

For microscopes, assuming the object is at the focal point, the resolving power is given by

$$\text{RP} = s = f\theta = \frac{1.22\lambda f}{D}.$$

Resolution of Telescopes and Microscopes; the λ Limit

Example : Telescope resolution (radio wave vs. visible light).

What is the theoretical minimum angular separation of two stars that can just be resolved by (a) the 200-inch telescope on Palomar Mountain; and (b) the Arecibo radio telescope, whose diameter is 300 m and whose radius of curvature is also 300 m. Assume λ = 550 nm for the visible-light telescope in part (a), and λ = 4 cm (the shortest wavelength at which the radio telescope has been operated) in part (b).

Resolution of Telescopes and Microscopes; the λ Limit

Typically, the focal length of a microscope lens is half its diameter, which shows that *it is not possible to resolve details smaller than the wavelength being used:*

$$\mathrm{RP} \approx \frac{\lambda}{2}.$$

Resolution of the Human Eye and Useful Magnification

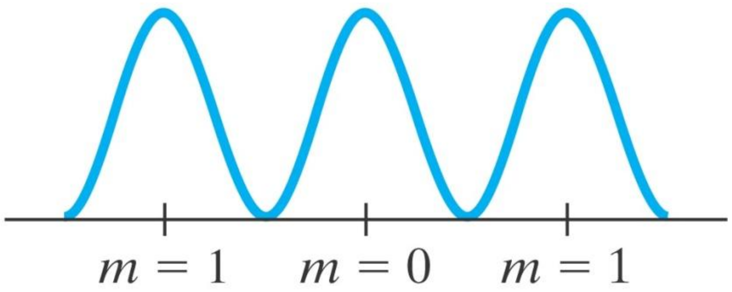
The human eye can resolve objects that are about 1 cm apart at a distance of 20 m, or 0.1 mm apart at the near point.

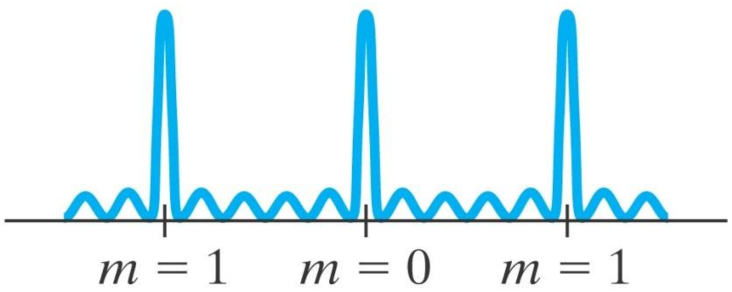
This limits the useful magnification of a light microscope to about 500x–1000x.

Diffraction Grating

A diffraction grating consists of a large number of equally spaced narrow slits or lines. A transmission grating has slits, while a reflection grating has lines that reflect light.

The more lines or slits there are, the narrower the peaks.

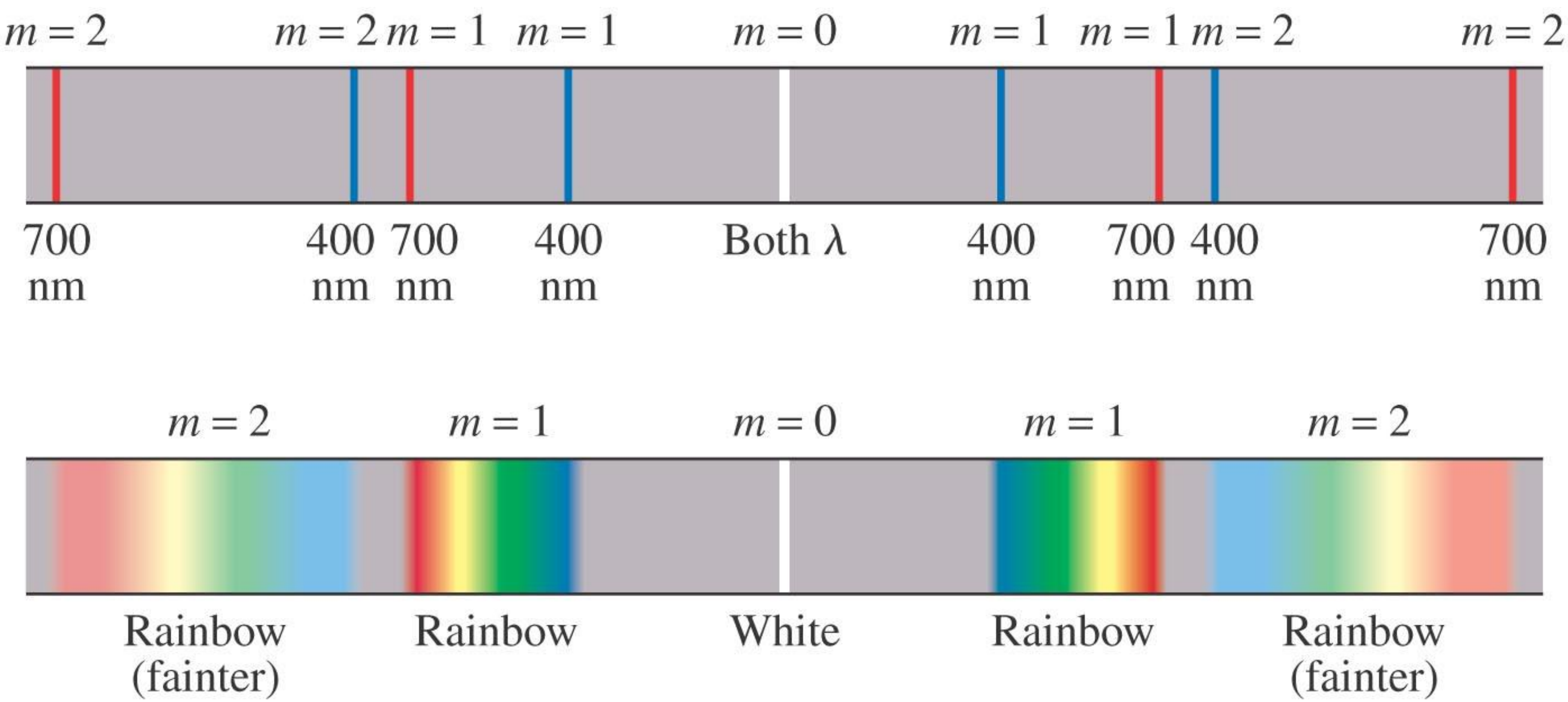




Diffraction Grating

The maxima of the diffraction pattern are defined by

$$\sin\theta = \frac{m\lambda}{d}, \qquad m = 0, 1, 2, \cdots \qquad \begin{bmatrix}\text{diffraction grating,}\\ \text{principal maxima}\end{bmatrix}$$



Diffraction Grating

Example : Diffraction grating: lines.

Determine the angular positions of the first- and second-order maxima for light of wavelength 400 nm and 700 nm incident on a grating containing 10,000 lines/cm.

Example : Spectra overlap.

White light containing wavelengths from 400 nm to 750 nm strikes a grating containing 4000 lines/cm. Show that the blue at $\lambda = 450$ nm of the third-order spectrum overlaps the red at 700 nm of the second order.

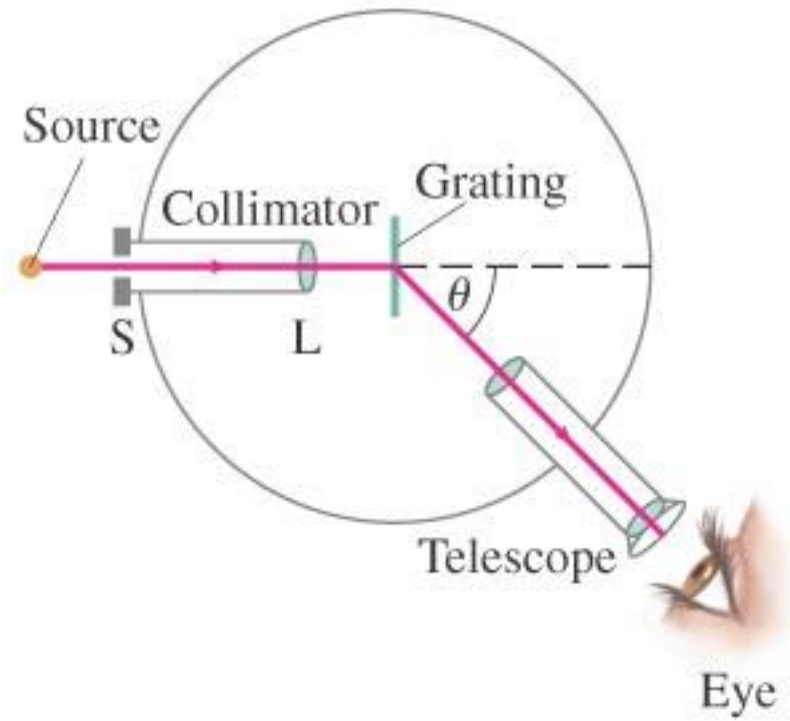
Diffraction Grating

Conceptual Example: Compact disk.

When you look at the surface of a music CD, you see the colors of a rainbow. (a) Estimate the distance between the curved lines (to be read by the laser). (b) Estimate the distance between lines, noting that a CD contains at most 80 min of music, that it rotates at speeds from 200 to 500 rev/min, and that 2/3 of its 6-cm radius contains the lines.

The Spectrometer and Spectroscopy

A spectrometer makes accurate measurements of wavelengths using a diffraction grating or prism.



The wavelength can be determined to high accuracy by measuring the angle at which the light is diffracted:

$$\sin\theta = \frac{m\lambda}{d}, \qquad m = 0, 1, 2, \cdots \qquad \begin{bmatrix}\text{diffraction grating,} \\ \text{principal maxima}\end{bmatrix}$$

The Spectrometer and Spectroscopy

Atoms and molecules can be identified when they are in a thin gas through their characteristic emission lines.

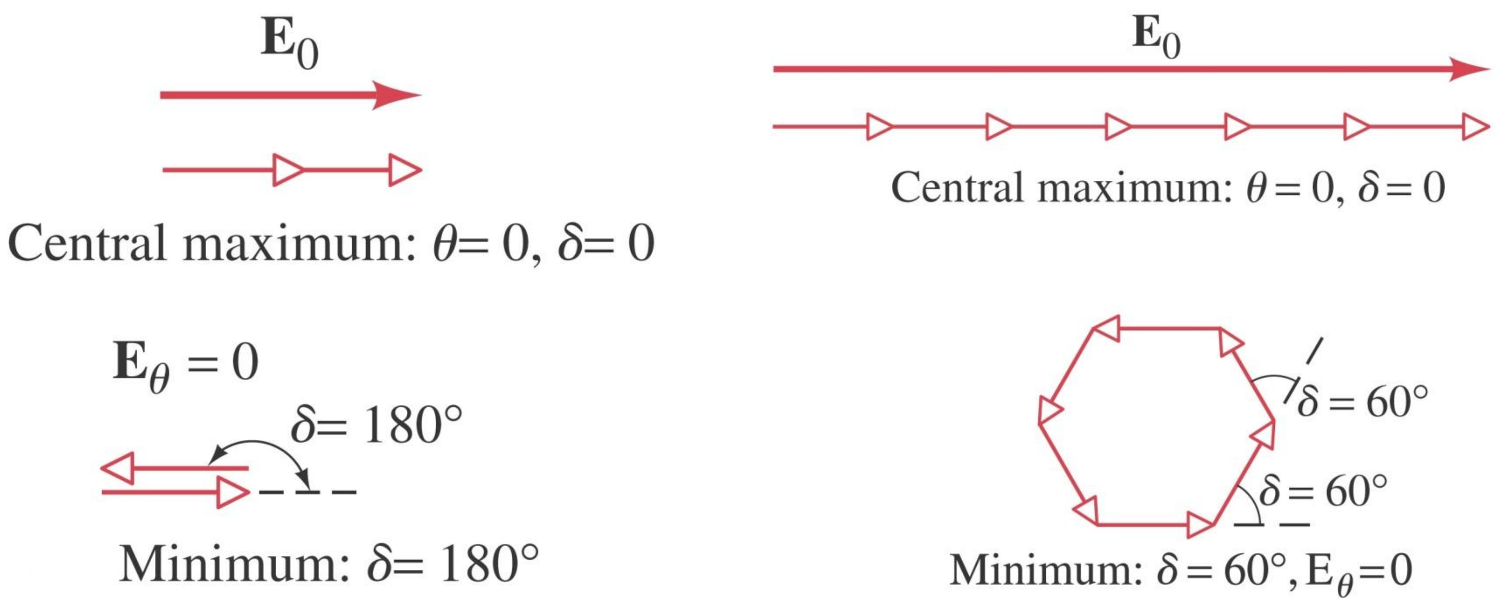
The Spectrometer and Spectroscopy

Example : Hydrogen spectrum.

Light emitted by hot hydrogen gas is observed with a spectroscope using a diffraction grating having 1.00 x 10^4 lines/cm. The spectral lines nearest to the center (0) are a violet line at 24.2°, a blue line at 25.7°, a blue-green line at 29.1°, and a red line at 41.0° from the center. What are the wavelengths of these spectral lines of hydrogen?

Peak Widths and Resolving Power for a Diffraction Grating

These two sets of diagrams show the phasor relationships at the central maximum and at the first minimum for gratings of two and six slits.



Peak Widths and Resolving Power for a Diffraction Grating

As the number of slits becomes large, the width of the central maximum becomes very narrow:

$$\Delta\theta_0 = \frac{\lambda}{Nd}.$$

The resolving power of a diffraction grating is the minimum difference between wavelengths that can be distinguished:

$$R = \frac{\lambda}{\Delta\lambda} = Nm.$$

Peak Widths and Resolving Power for a Diffraction Grating

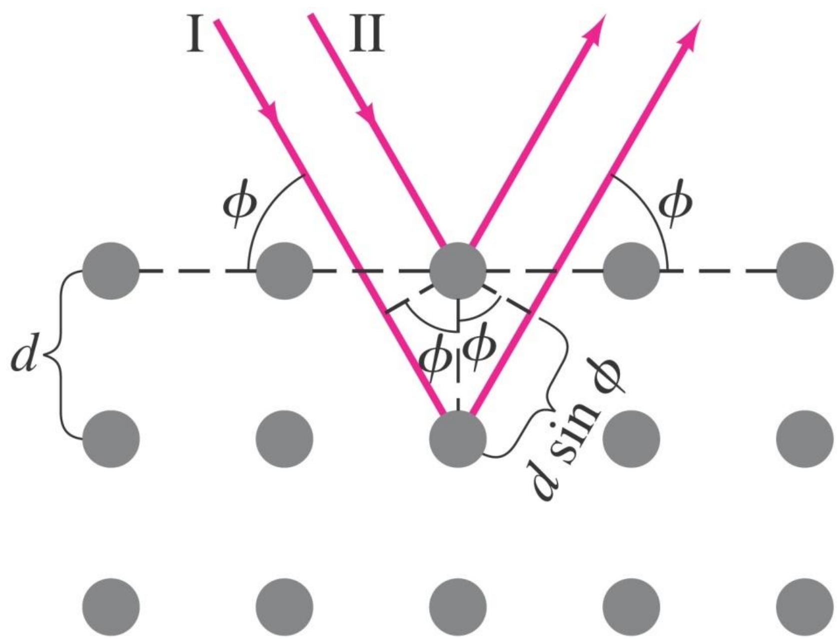
Example : Resolving two close lines.

Yellow sodium light, which consists of two wavelengths, λ_1 = 589.00 nm and λ_2 = 589.59 nm, falls on a diffraction grating. Determine (a) the maximum order m that will be present for sodium light, and (b) the width of grating necessary to resolve the two sodium lines.

X-Rays and X-Ray Diffraction

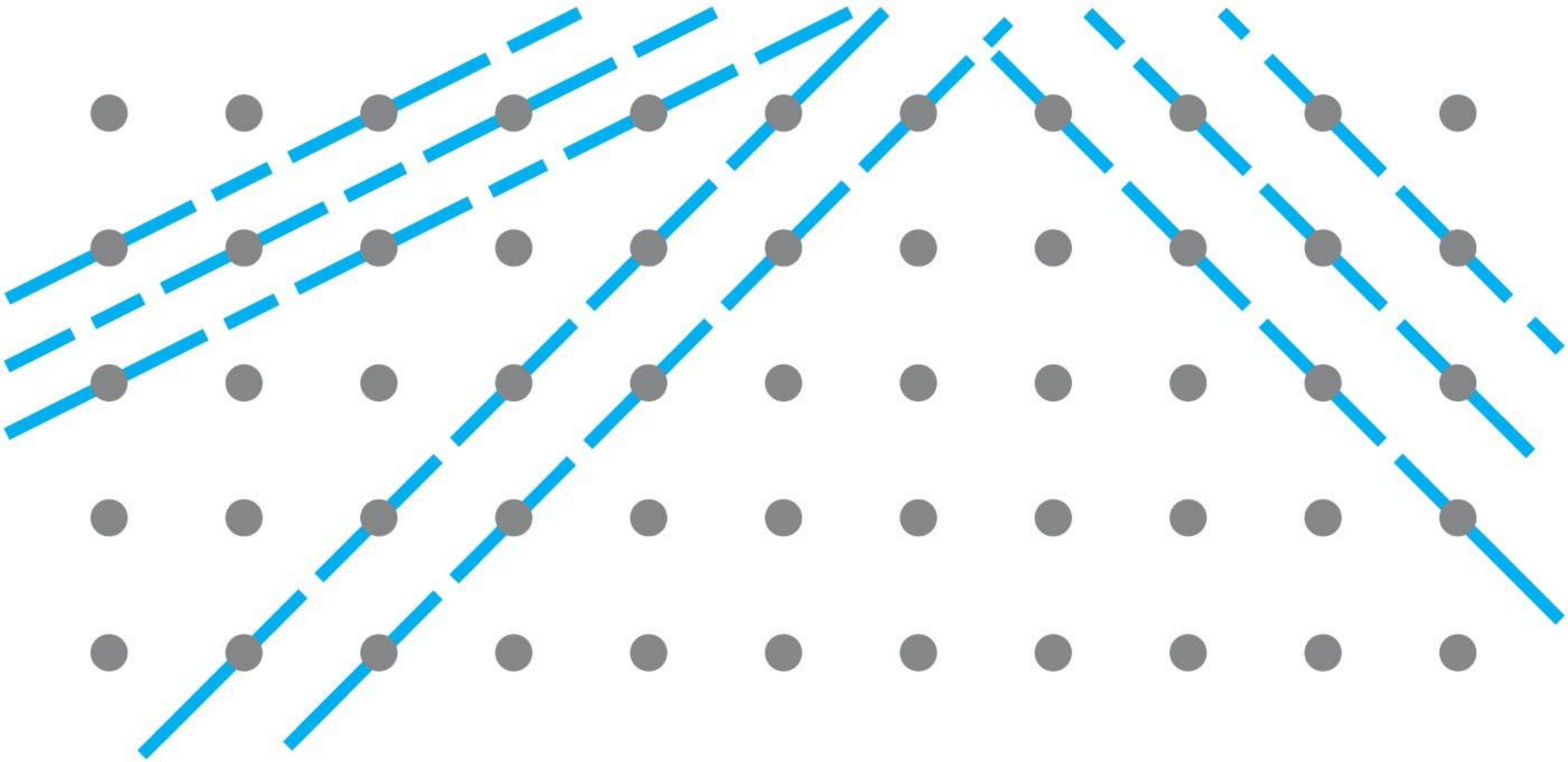
The wavelengths of X-rays are very short. Diffraction experiments are impossible to do with conventional diffraction gratings.

Crystals have spacing between their layers that is ideal for diffracting X-rays.



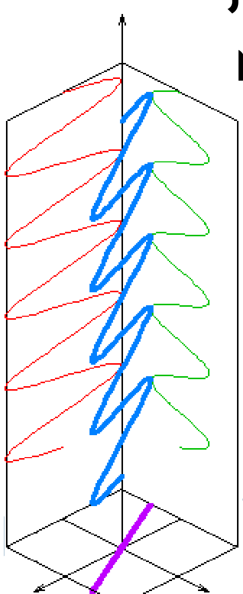
X-Rays and X-Ray Diffraction

X-ray diffraction is now used to study the internal structure of crystals; this is how the helical structure of DNA was determined.

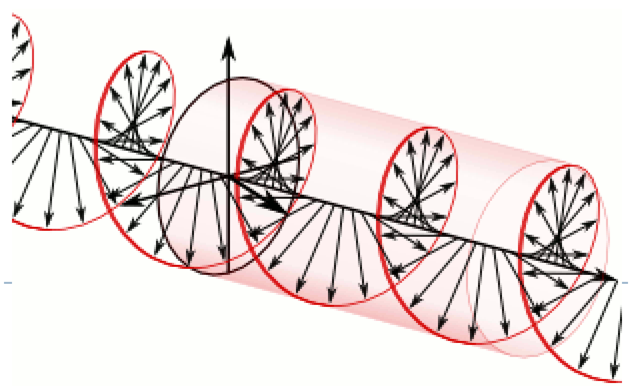


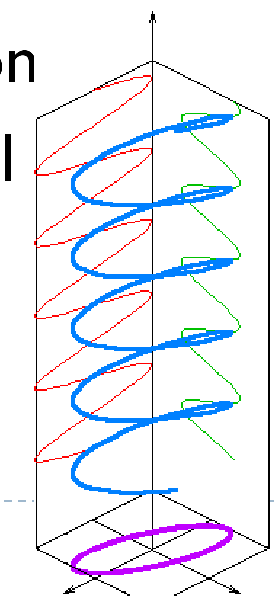
Polarization of light

- One of the physical properties of light is that it can be polarized. Polarization is a measurement of the electromagnetic field's alignment. In the bottom right hand corner figure, the electric field (in red) is vertically polarized. Think of a throwing a Frisbee at a picket fence. In one orientation it will pass through, in another it will be rejected. This is similar to how sunglasses are able to ate glare by absorbing the polarized portion



Classification: linear, circular and elliptical

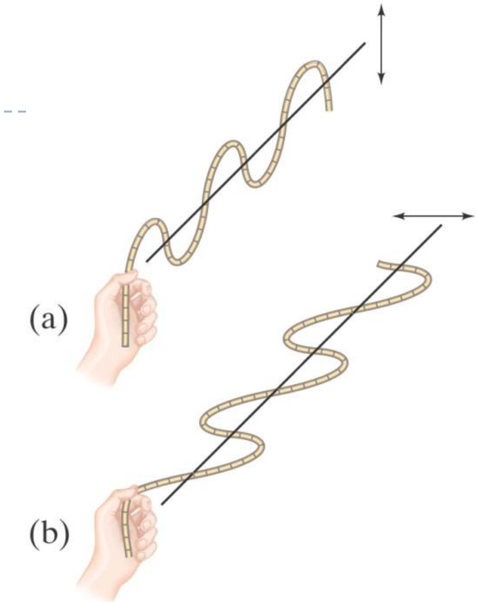


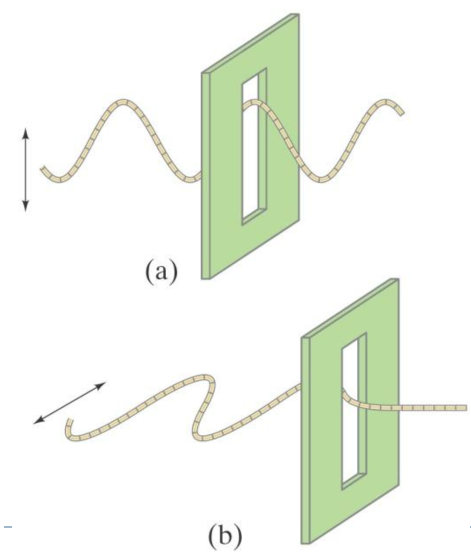


Polarization

Light is polarized when its electric fields oscillate in a single plane, rather than in any direction perpendicular to the direction of propagation.

Polarized light will not be transmitted through a polarized film whose axis is perpendicular to the polarization direction.

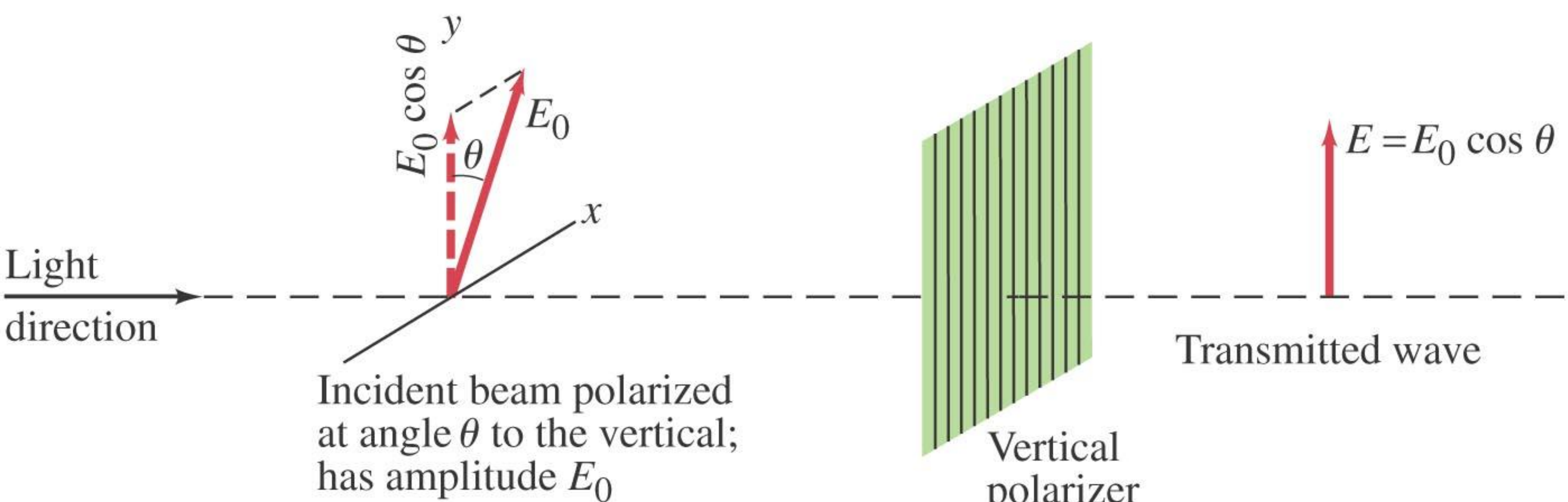




Polarization

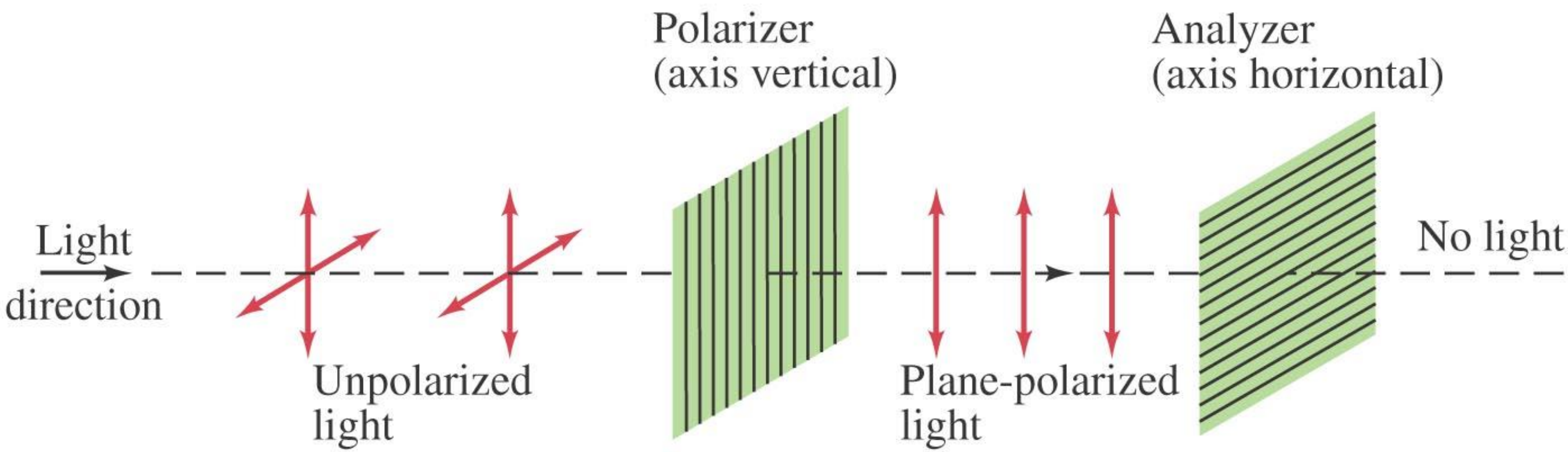
When light passes through a polarizer, only the component parallel to the polarization axis is transmitted. If the incoming light is plane-polarized, the outgoing intensity is:

$$I = I_0 \cos^2 \theta, \qquad \left[\begin{array}{c}\text{intensity of plane polarized} \\ \text{wave reduced by polarizer}\end{array}\right]$$



Polarization

This means that if initially unpolarized light passes through crossed polarizers, no light will get through the second one.



Polarization

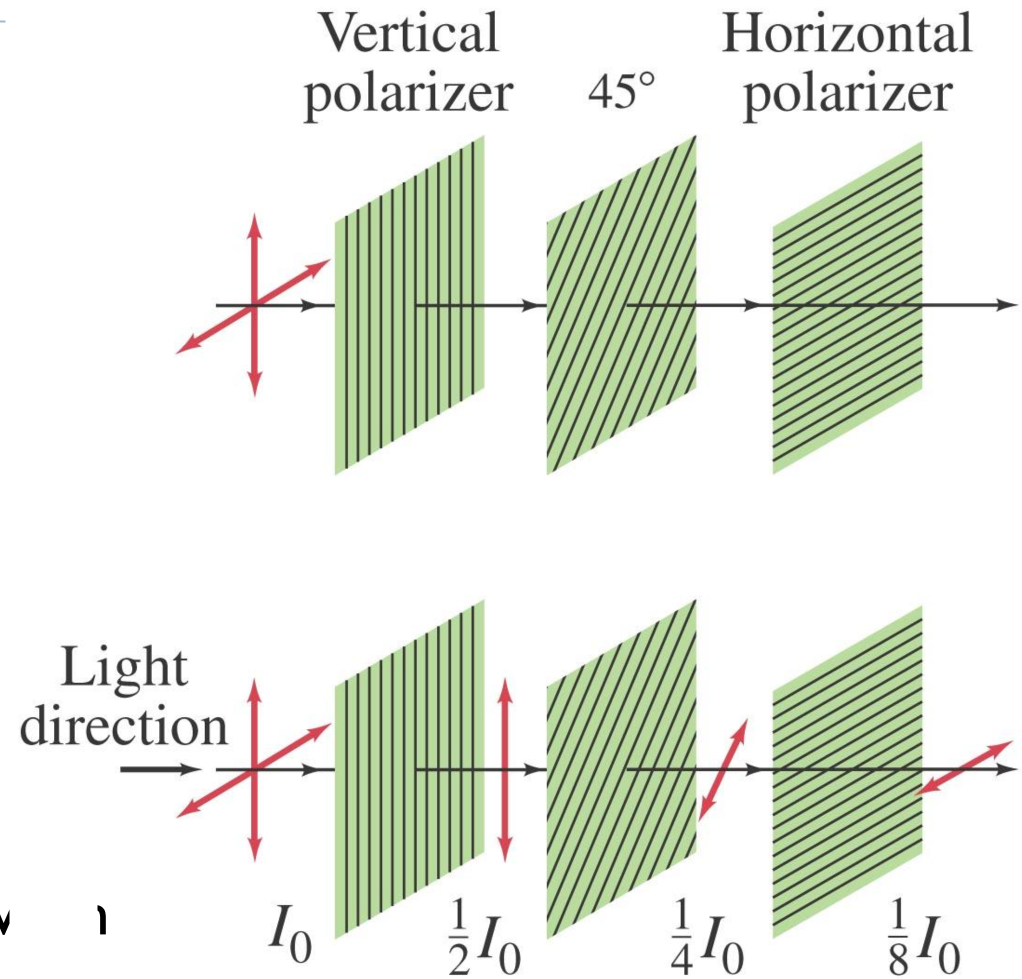
Example : Two Polaroids at 60 .

Unpolarized light passes through two Polaroids; the axis of one is vertical and that of the other is at 60 to the vertical. Describe the orientation and intensity of the transmitted light.

Polarization

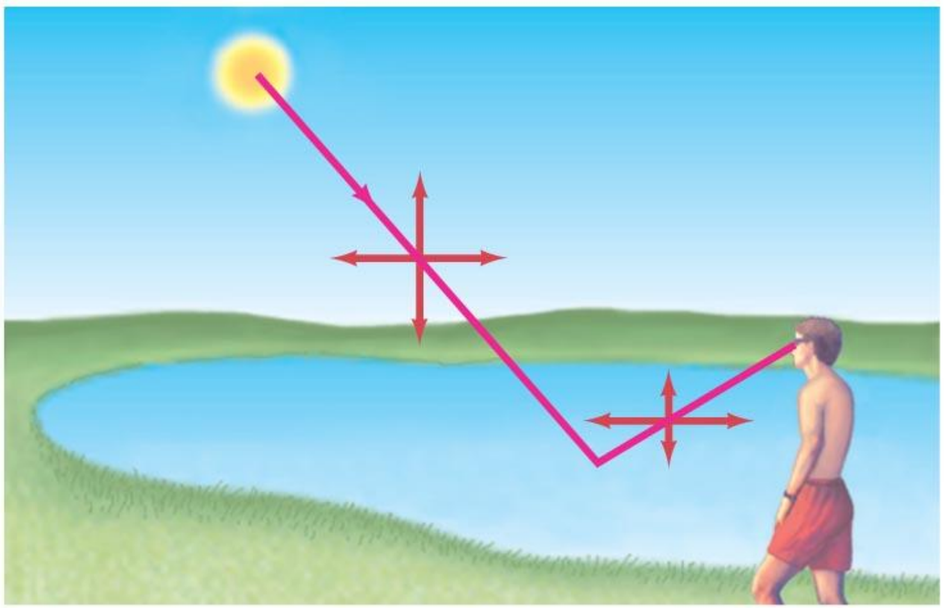
Conceptual Example : Three Polaroids.

When unpolarized light falls on two crossed Polaroids (axes at 90°), no light passes through.
What happens if a third Polaroid, with axis at 45° to each of the other two, is placed betw
them?



Polarization

Light is also partially polarized after reflecting from a nonmetallic surface. At a special angle, called the polarizing angle or Brewster's angle, the polarization is 100%:



$$\tan\theta_p = \frac{n_2}{n_1}.$$

Example : Polarizing angle.

(a) At what incident angle is sunlight reflected from a lake plane-polarized? (b) What is the refraction angle?

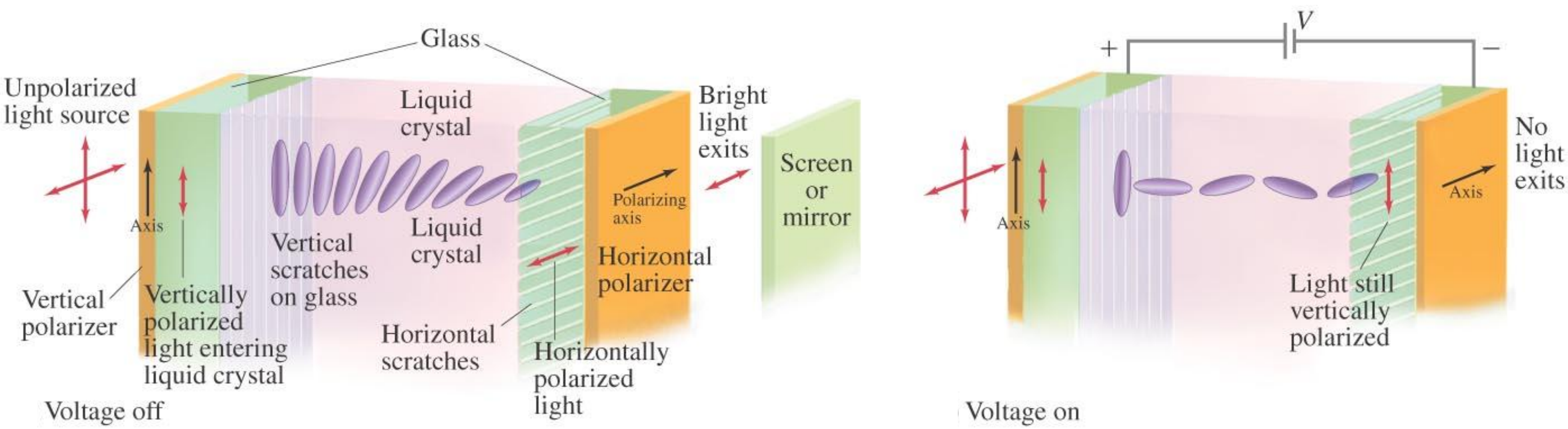
Liquid Crystal Displays (LCD)

Liquid crystals are unpolarized in the absence of an external voltage, and will easily transmit light. When an external voltage is applied, the crystals become polarized and no longer transmit; they appear dark.

Liquid crystals can be found in many familiar applications, such as calculators and digital watches.

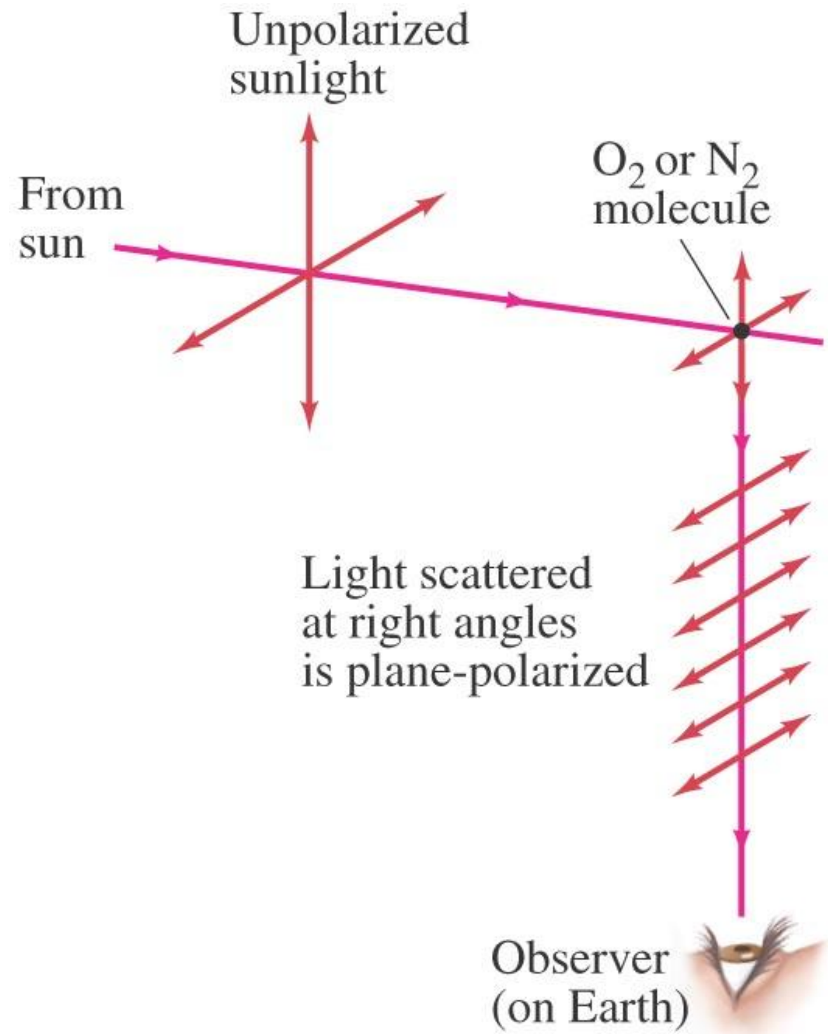
Liquid Crystal Displays (LCD)

This particular type of liquid crystal, called a twisted crystal, shows how the crystal passes light when the voltage is off but not when it is on.



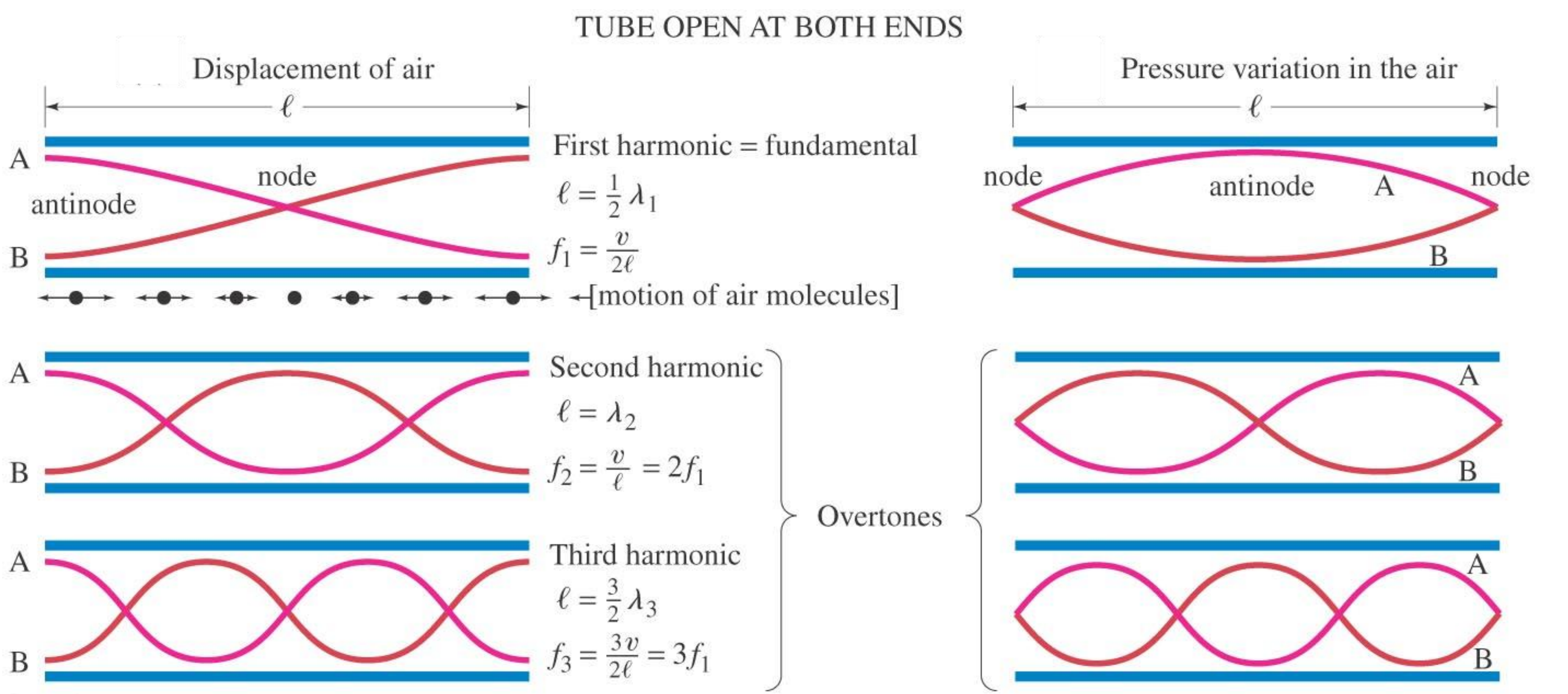
Scattering of Light by the Atmosphere

Skylight is partially polarized due to scattering from molecules in the air. The amount of polarization depends on the angle that your line of sight makes with the Sun.



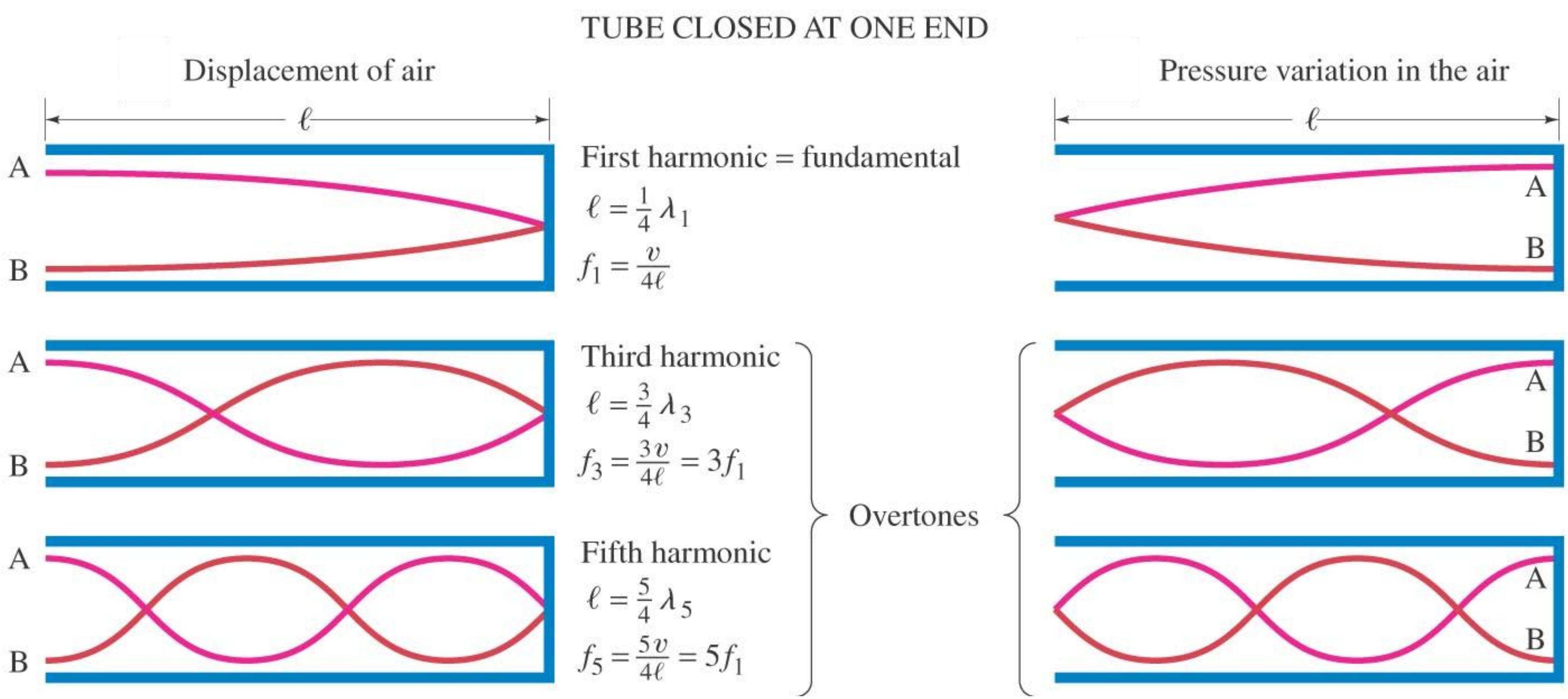
Sources of Sound: Vibrating Strings and Air Columns

A tube open at both ends (most wind instruments) has pressure nodes, and therefore displacement antinodes, at the ends.

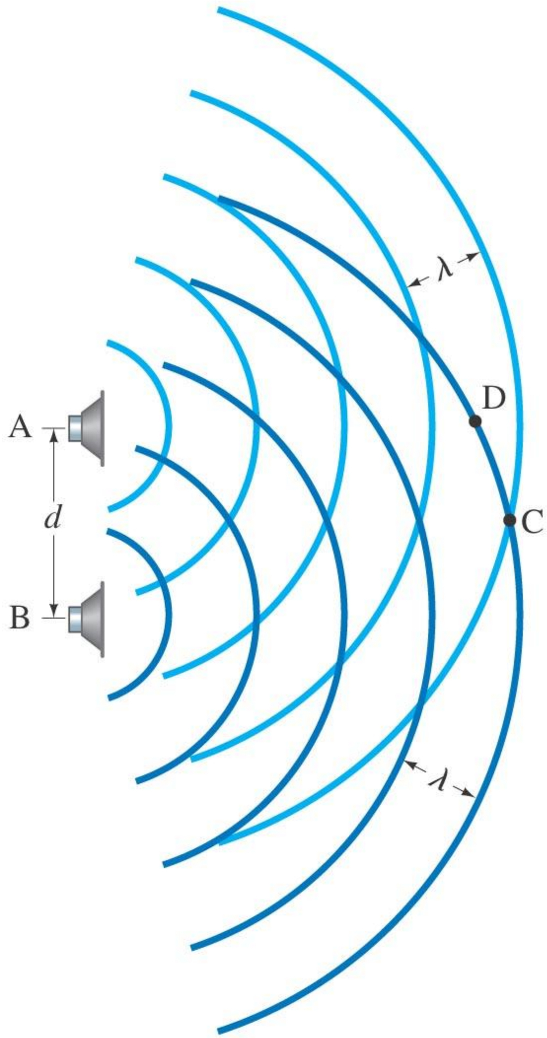


Sources of Sound: Vibrating Strings and Air Columns

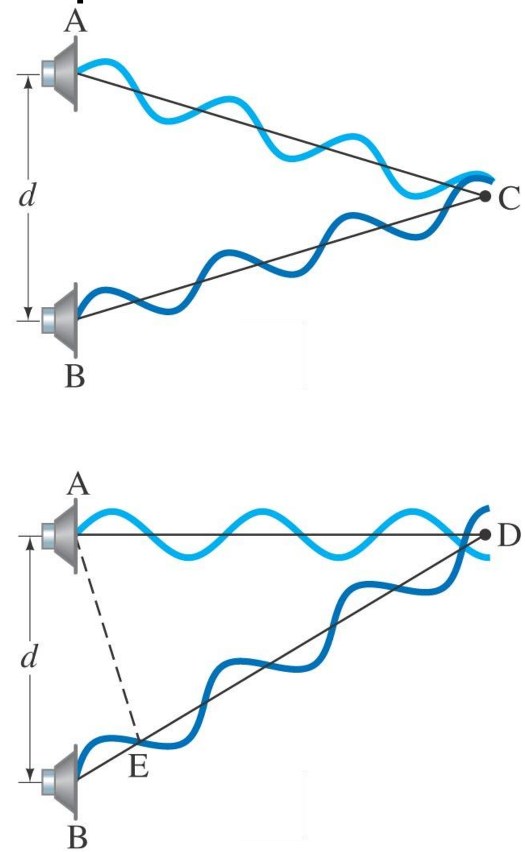
A tube closed at one end (some organ pipes) has a displacement node (and pressure antinode) at the closed end.



Interference of Sound Waves; Beats

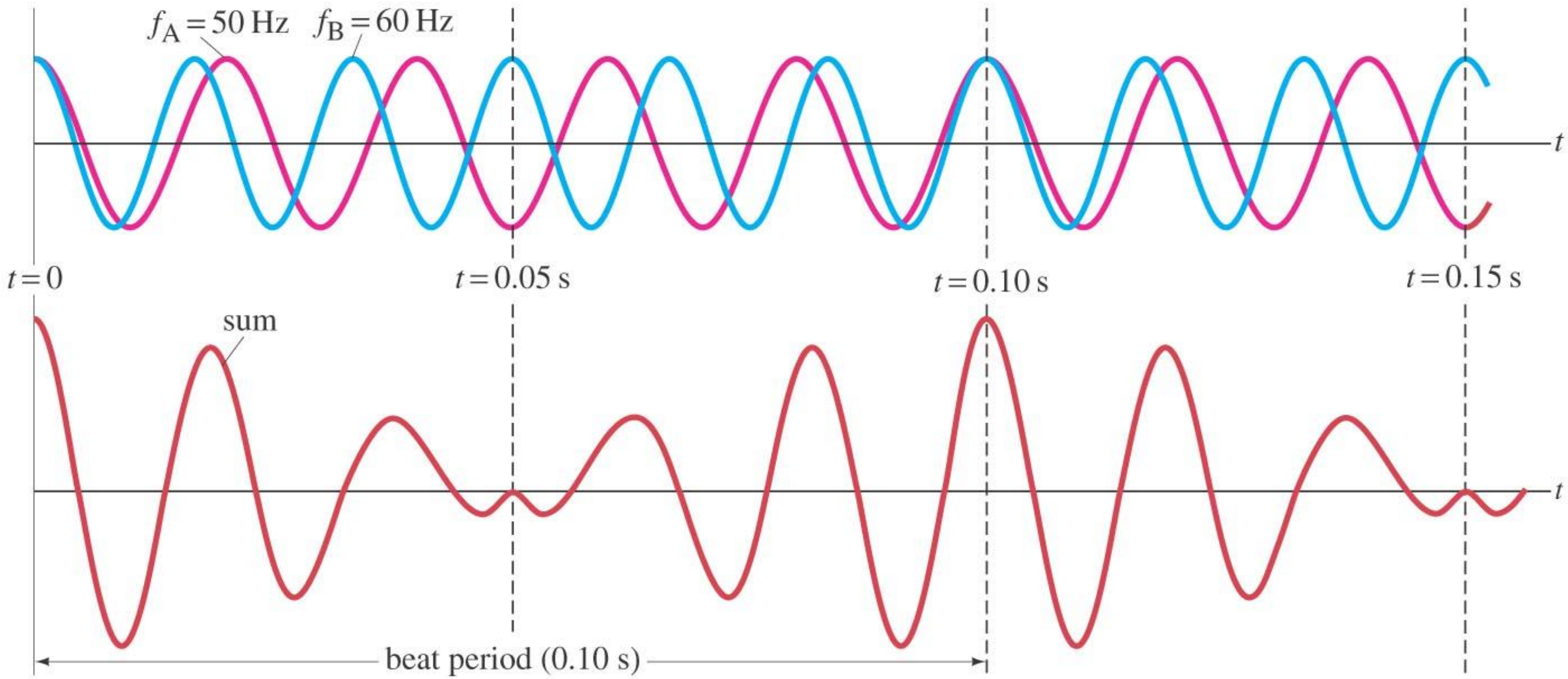


Sound waves interfere in the same way that other waves do in space.



Interference of Sound Waves; Beats

Waves can also interfere in time, causing a phenomenon called beats. **Beats** are the slow "envelope" around two waves that are relatively close in frequency.



Interference of Sound Waves; Beats

If we consider two waves of the same amplitude and phase, with different frequencies, we can find the beat frequency

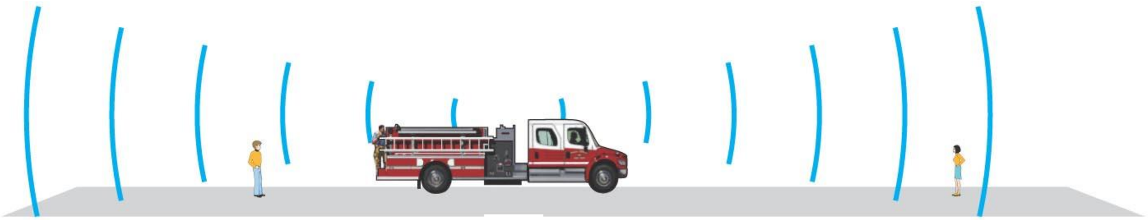
$$D = \left[2A\cos 2\pi\left(\frac{f_1 - f_2}{2}\right)t\right]\sin 2\pi\left(\frac{f_1 + f_2}{2}\right)t.$$

This represents a wave vibrating at the average frequency, with an "envelope" at the difference of the frequencies.

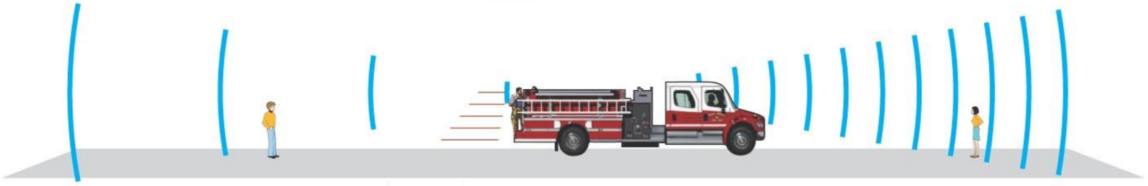
Doppler Effect

The Doppler effect occurs when a source of sound is moving with respect to an observer.

A source moving toward an observer appears to have a higher frequency and shorter wavelength; a source moving away from an observer appears to have a lower frequency and longer wavelength.

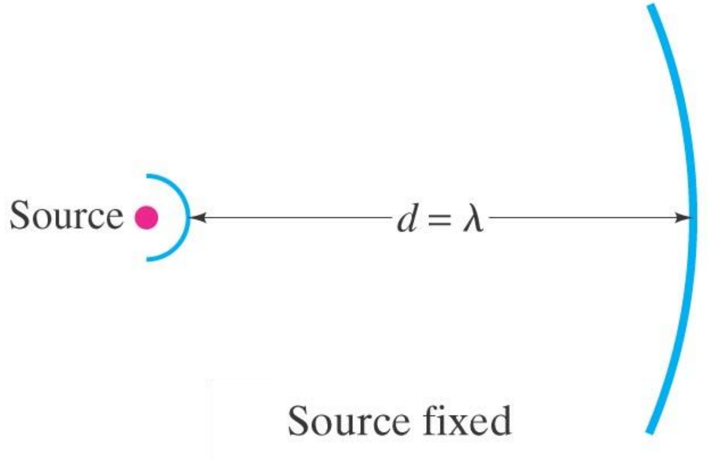


At rest

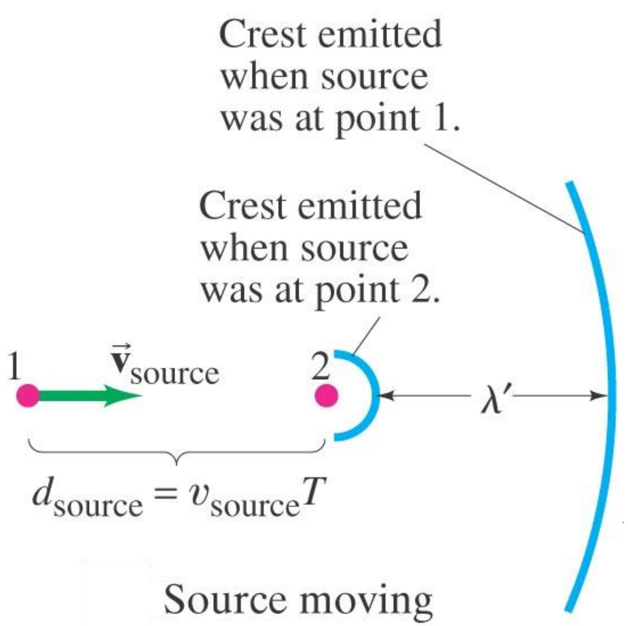


Fire truck moving

Doppler Effect



If we can figure out what the change in the wavelength is, we also know the change in the frequency.



Doppler Effect

The change in the frequency is given by:

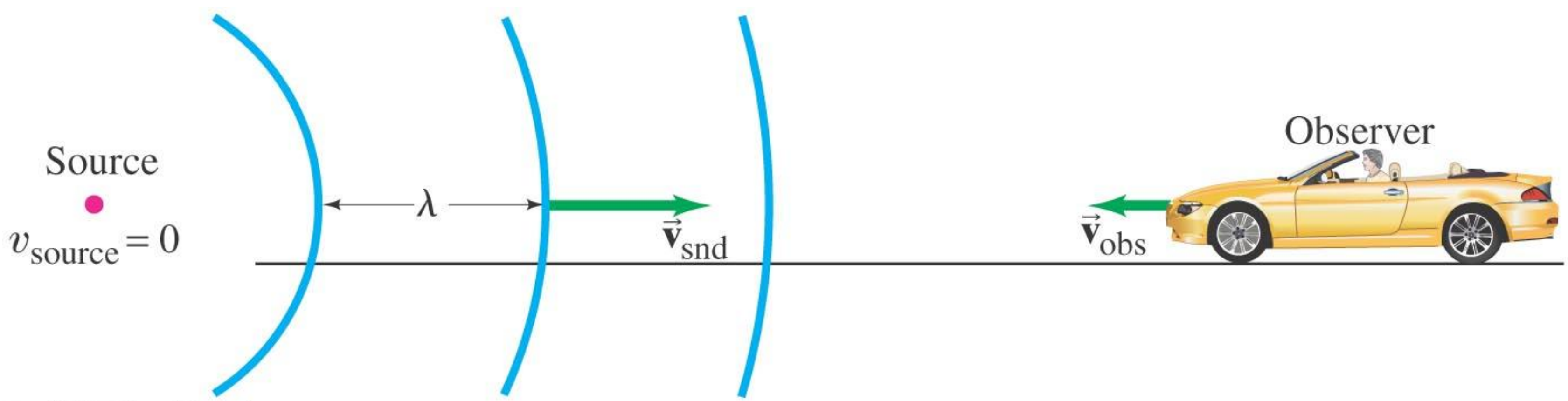
$$f' = \frac{f}{\left(1 - \frac{v_{\text{source}}}{v_{\text{snd}}}\right)}.$$

If the source is moving away from the observer:

$$f' = \frac{f}{\left(1 + \frac{v_{\text{source}}}{v_{\text{snd}}}\right)}.$$

Doppler Effect

If the observer is moving with respect to the source, things are a bit different. The wavelength remains the same, but the wave speed is different for the observer.



Doppler Effect

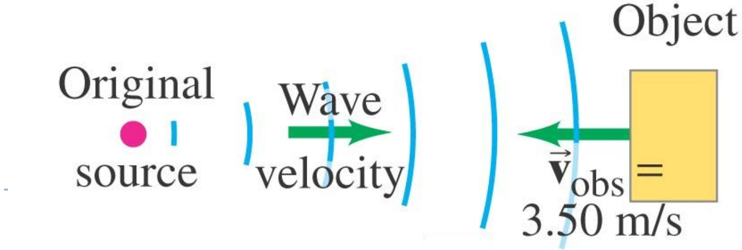
We find, for an observer moving toward a stationary source:

$$f' = \left(1 + \frac{v_{\mathrm{obs}}}{v_{\mathrm{snd}}}\right) f.$$

And if the observer is moving away:

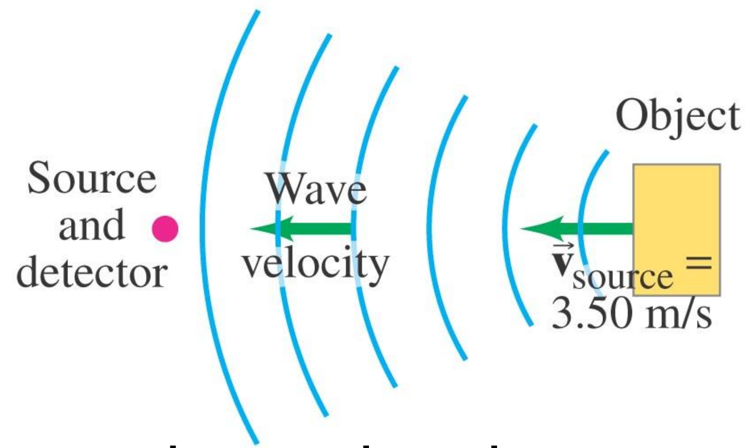
$$f' = \left(1 - \frac{v_{\mathrm{obs}}}{v_{\mathrm{snd}}}\right) f.$$

Doppler Effect



Two Doppler shifts.

A 5000-Hz sound wave is emitted by a stationary source. This sound wave reflects from an object moving toward the source. What is the frequency of the wave reflected by the moving object as detected by a detector at rest near the source?



All four equations for the Doppler effect can be combined into one; you just have to keep track of the signs!

$$f' = f\left(\frac{v_{\mathrm{snd}} \pm v_{\mathrm{obs}}}{v_{\mathrm{snd}} \mp v_{\mathrm{source}}}\right).$$

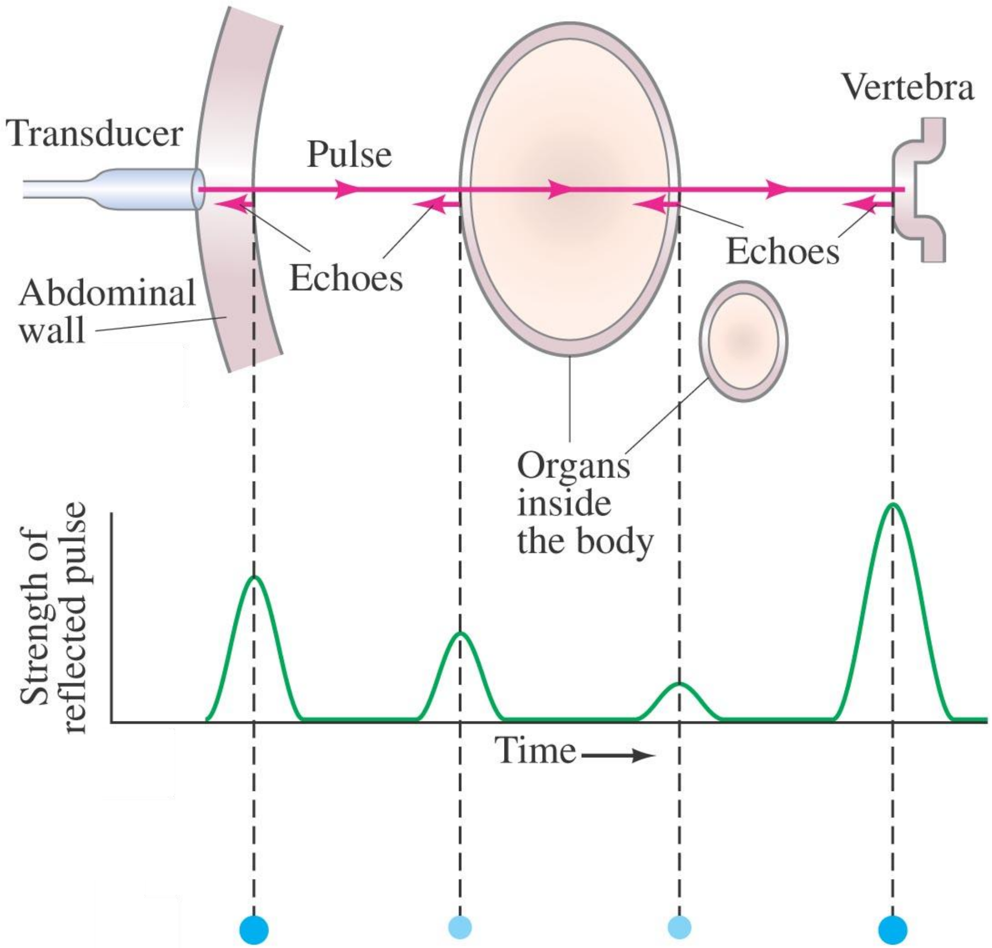
Applications: Sonar, Ultrasound, and Medical Imaging

Sonar is used to locate objects underwater by measuring the time it takes a sound pulse to reflect back to the receiver.

Similar techniques can be used to learn about the internal structure of the Earth.

Sonar usually uses ultrasound waves, as the shorter wavelengths are less likely to be diffracted by obstacles.

Applications: Sonar, Ultrasound, and Medical Imaging



Ultrasound is also used for medical imaging. Repeated traces are made as the transducer is moved, and a complete picture is built.

Applications: Sonar, Ultrasound, and Medical Imaging

This is an ultrasound image of a human fetus, showing great detail.

More applications of the Doppler Effect

The Doppler effect for electromagnetic waves such as light is of great use in astronomy. The belief that the universe is expanding is based in part upon observations of electromagnetic waves emitted by stars in distant galaxies. Furthermore, specific information about stars within galaxies can be determined by application of the Doppler effect. Galaxies are clusters of stars that typically rotate about some center of mass point.

Electromagnetic radiation emitted by such stars in a distant galaxy would appear to be shifted downward in frequency (a *red shift*) if the star is rotating in its cluster in a direction that is away from the Earth.
On the other hand, there is an upward shift in frequency (a *blue shift*) of such observed radiation if the star is rotating in a direction that is towards the Earth.

The Doppler effect is used in some types of radar, to measure the velocity of detected objects

Doppler effect Summary

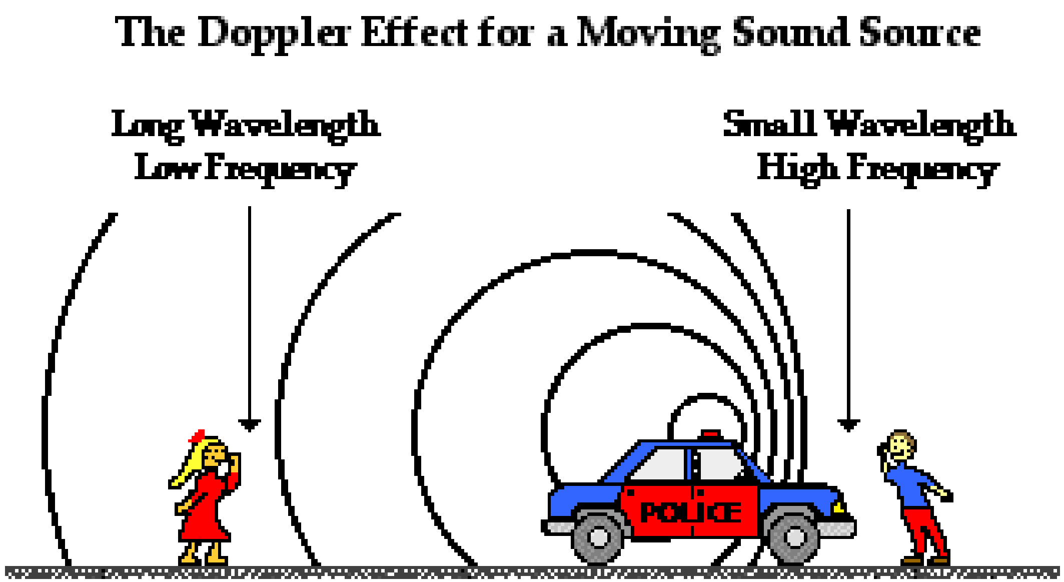
- The Doppler effect is observed whenever the source of waves is moving with respect to an observer.
- The Doppler effect can be described as the effect produced by a moving source of waves in which there is an apparent upward shift in frequency for observers towards whom the source is approaching and an apparent downward shift in frequency for observers from whom the source is receding. It is important to note that the effect does not result because of an <u>actual</u> change in the frequency of the source.
- The perceived frequency (f') is related to the actual frequency (f_0) and the relative speeds of the source (v_s), observer (v_o), and the speed (v) of waves in the medium by

$$f' = f_0 \frac{v \pm v_0}{v \pm v_s}$$

The Doppler Effect cont'd

- The choice of using the plus (+) or minus (-) sign is made according to the convention that if the source and observer are moving *towards* each other the perceived frequency ($f\,'$) is *higher* than the actual frequency (f_0). Likewise, if the source and observer are moving *away from* each other the perceived frequency ($f\,'$) is *lower* than the actual frequency (f_0).
- The Doppler effect holds true for all types of waves including light (and other electromagnetic waves).
- The Doppler effect for light waves is usually described in terms of colors rather than frequency. A red shift occurs when the source and observer are moving away from each other, and a blue shift occurs when the source and observer are moving towards each other. The red shift of light from remote galaxies is proof that the universe is expanding.

Doppler effect



Doppler effect Problem 1

- Problem 1
- A) Compare the shift frequency if a 2300Hz source is moving toward you at 18m/s, versus you moving toward it at the same speed.
- B)Repeat the calculation for 160m/s
- C) Repeat the calculation for 320m/s
- What can you conclude about the asymmetry of the Doppler formulae
- D) Show that at low speeds (relative to the speed of sound), the two formulae – source approaching and detector approaching- yield the same result.

Doppler effect Problem 1 Solution

- (*a*) For the 18 m/s relative velocity:
- $$f'_{\substack{\text{source}\\\text{moving}}} = f\,\frac{1}{\left(1-\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right)} = 2300\text{ Hz}\;\frac{1}{\left(1-\dfrac{18\,\text{m/s}}{343\,\text{m/s}}\right)} = 2427\,\text{Hz} \approx \boxed{2430\,\text{Hz}}$$
- $$f'_{\substack{\text{observer}\\\text{moving}}} = f\left(1+\frac{v_{\text{src}}}{v_{\text{snd}}}\right) = 2300\text{ Hz}\left(1+\frac{18\,\text{m/s}}{343\,\text{m/s}}\right) = 2421\,\text{Hz} \approx \boxed{2420\,\text{Hz}}$$
- The frequency shifts are slightly different, with . $f'_{\substack{\text{source}\\\text{moving}}} > f'_{\substack{\text{observer}\\\text{moving}}}$
- The two frequencies are close, but they are not identical. As a means of comparison, calculate the spread in frequencies divided by the original frequency.
- $$\frac{f'_{\substack{\text{source}\\\text{moving}}} - f'_{\substack{\text{observer}\\\text{moving}}}}{f_{\text{source}}} = \frac{2427\,\text{Hz} - 2421\,\text{Hz}}{2300\,\text{Hz}} = 0.0026 = 0.26\%$$

Doppler effect Problem 1 Solution cont'd

- (*b*) For the 160 m/s relative velocity:

$$f'_{\substack{\text{source}\\\text{moving}}} = f\,\frac{1}{\left(1-\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right)} = 2300\ \text{Hz}\ \frac{1}{\left(1-\dfrac{160\,\text{m/s}}{343\,\text{m/s}}\right)} = 4311\,\text{Hz} \approx \boxed{4310\,\text{Hz}}$$

$$f'_{\substack{\text{observer}\\\text{moving}}} = f\left(1+\frac{v_{\text{src}}}{v_{\text{snd}}}\right) = 2300\ \text{Hz}\left(1+\frac{160\,\text{m/s}}{343\,\text{m/s}}\right) = 3372\ \text{Hz} \approx \boxed{3370\,\text{Hz}}$$

- The difference in the frequency shifts is much larger this time, still with $f'_{\substack{\text{source}\\\text{moving}}} > f'_{\substack{\text{observer}\\\text{moving}}}$
-

$$\frac{f'_{\substack{\text{source}\\\text{moving}}} - f'_{\substack{\text{observer}\\\text{moving}}}}{f_{\text{source}}} = \frac{4311\,\text{Hz} - 3372\,\text{Hz}}{2300\,\text{Hz}} = 0.4083 = 41\%$$

Doppler effect Problem 1 Solution cont'd

- (c) For the 320 m/s relative velocity:

$$f'_{\substack{\text{source}\\\text{moving}}} = f\frac{1}{\left(1-\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right)} = 2300\text{ Hz}\ \frac{1}{\left(1-\dfrac{320\text{ m/s}}{343\text{ m/s}}\right)} = \boxed{34,300\text{ Hz}}$$

$$f'_{\substack{\text{observer}\\\text{moving}}} = f\left(1+\frac{v_{\text{src}}}{v_{\text{snd}}}\right) = 2300\text{ Hz}\ \left(1+\frac{320\text{ m/s}}{343\text{ m/s}}\right) = 4446\text{ Hz} \approx \boxed{4450\text{ Hz}}$$

- The difference in the frequency shifts is quite large, still with . $f'_{\substack{\text{source}\\\text{moving}}} > f'_{\substack{\text{observer}\\\text{moving}}}$

- $$\frac{f'_{\substack{\text{source}\\\text{moving}}} - f'_{\substack{\text{observer}\\\text{moving}}}}{f_{\text{source}}} = \frac{34,300\text{ Hz} - 4446\text{ Hz}}{2300\text{ Hz}} = 12.98 = 1300\%$$

Doppler effect Problem 1 Solution cont'd

- (*d*) The Doppler formulas are asymmetric, with a larger shift for the moving source than for the moving observer, when the two are getting closer to each other. In the following derivation, assume and use the binomial expansion.

$$f'_{\substack{\text{source}\\\text{moving}}} = f\,\frac{1}{\left(1-\dfrac{v_{\text{src}}}{v_{\text{snd}}}\right)} = f\left(1-\frac{v_{\text{src}}}{v_{\text{snd}}}\right)^{-1} \approx f\left(1+\frac{v_{\text{src}}}{v_{\text{snd}}}\right) = f'_{\substack{\text{observer}\\\text{moving}}}$$

Doppler effect Problem 2

- The Doppler effect using ultrasonic waves of frequency 2.25X10^6Hz is used to monitor the heartbeat of a fetus. A maximum beat frequency of 260Hz is observed. Assuming that the speed of sound in tissue is 1.54x10^3m/s, calculate the maximum velocity of the surface of the beating heart.

Doppler effect Problem 2 Solution

- The maximum Doppler shift occurs when the heart has its maximum velocity. Assume that the heart is moving away from the original source of sound. The beats arise from the combining of the original 2.25 MHz frequency with the reflected signal which has been Doppler shifted. There are two Doppler shifts – one for the heart receiving the original signal (observer moving away from stationary source) and one for the detector receiving the reflected signal (source moving away from stationary observer).

Doppler effect Problem 2 Solution cont'd

$$f'_{\text{heart}} = f_{\text{original}}\left(1 - \frac{v_{\text{heart}}}{v_{\text{snd}}}\right) \qquad f''_{\text{detector}} = \frac{f'_{\text{heart}}}{\left(1 + \frac{v_{\text{heart}}}{v_{\text{snd}}}\right)} = f_{\text{original}}\frac{\left(1 - \frac{v_{\text{heart}}}{v_{\text{snd}}}\right)}{\left(1 + \frac{v_{\text{heart}}}{v_{\text{snd}}}\right)} = f_{\text{original}}\frac{v_{\text{snd}} - v_{\text{heart}}}{v_{\text{snd}} + v_{\text{heart}}}$$

$$\Delta f = f_{\text{original}} - f''_{\text{detector}} = f_{\text{original}} - f_{\text{original}}\frac{(v_{\text{snd}} - v_{\text{blood}})}{(v_{\text{snd}} + v_{\text{blood}})} = f_{\text{original}}\frac{2v_{\text{blood}}}{(v_{\text{snd}} + v_{\text{blood}})} \rightarrow$$

$$v_{\text{blood}} = v_{\text{snd}}\frac{\Delta f}{2f_{\text{original}} - \Delta f} = 1.54\times10^{3}\ \text{m/s}\ \frac{260\ \text{Hz}}{2\ \ 2.25\times10^{6}\ \text{Hz}\ \ -260\ \text{Hz}} = \boxed{8.9\times10^{-2}\ \text{m/s}}$$

Doppler effect Problem 2 Solution cont'd

- If instead we had assumed that the heart was moving towards the original source of sound, we would
- get $$v_{\text{blood}} = v_{\text{snd}} \frac{\Delta f}{2 f_{\text{original}} + \Delta f}$$
- Since the beat frequency is much smaller than the original frequency, the term in the denominator does not significantly affect the answer.

END

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Ocean boat

- A wave on the surface of the ocean with wavelength 44m is moving at a speed of 18m/s relative to the ocean floor. If, on this stretch of the ocean surface, a power boat is moving at 15m/s (relative to the ocean floor), how often does the boat encounter a wave crest, if the boat is traveling a) west, b) east.?

Doppler effect Problem 2 Solution

- The ocean wave has and relative to the ocean floor. The frequency of the ocean wave is then
- (*a*) For the boat traveling west, the boat will encounter a Doppler shifted frequency, for an observer moving towards a stationary source. The speed represents the speed of the waves in the stationary medium, and so corresponds to the speed of sound in the Doppler formula. The time between encountering waves is the period of the Doppler shifted frequency.

$$f'_{\substack{\text{observer}\\\text{moving}}} = \left(1 + \frac{v_{\text{obs}}}{v_{\text{snd}}}\right) f = \left(1 + \frac{15\,\text{m/s}}{18\,\text{m/s}}\right) 0.409\,\text{Hz} = 0.750\,\text{Hz} \rightarrow$$

$$T = \frac{1}{f} = \frac{1}{0.750\,\text{Hz}} = \boxed{1.3\,\text{s}}$$

Solution Cont'd

- (*b*) For the boat traveling east, the boat will encounter a Doppler shifted frequency, for an observer moving away from a stationary source.

$$f'_{\substack{\text{observer}\\\text{moving}}} = \left(1 - \frac{v_{\text{obs}}}{v_{\text{snd}}}\right) f = \left(1 - \frac{15\,\text{m/s}}{18\,\text{m/s}}\right) 0.409\,\text{Hz} = 0.0682\,\text{Hz} \rightarrow$$

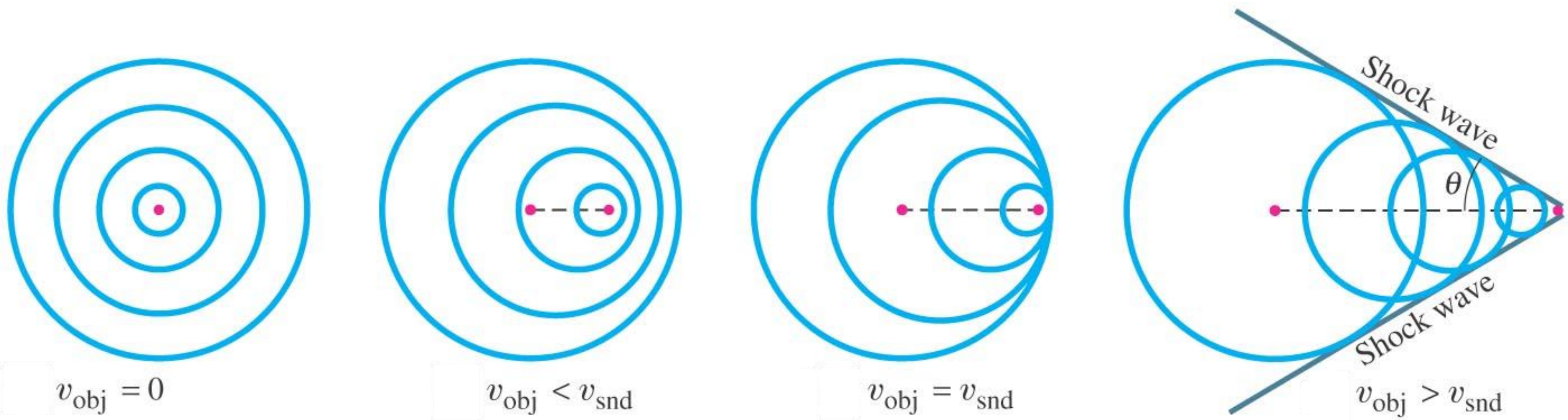
$$T = \frac{1}{f} = \frac{1}{0.0682\,\text{Hz}} = \boxed{15\,\text{s}}$$

Shock Waves and the Sonic Boom

If a source is moving faster than the wave speed in a medium, waves cannot keep up and a shock wave is formed.

The angle of the cone is:

$$\sin\theta = \frac{v_{\mathrm{snd}}}{v_{\mathrm{obj}}}.$$



Shock Waves and the Sonic Boom

Shock waves are analogous to the bow waves produced by a boat going faster than the wave speed in water.

Shock Waves and the Sonic Boom

Aircraft exceeding the speed of sound in air will produce two sonic booms, one from the front and one from the tail.