Lecture # 08: Technical Basis for Optical Instrumentation

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Sources/ Further reading:

Hecht, "Optics" 4th ed.

Raffel, Willert, Wereley, Kompenhans, "Particle image velocimetry: A practical guide" 2nd ed.

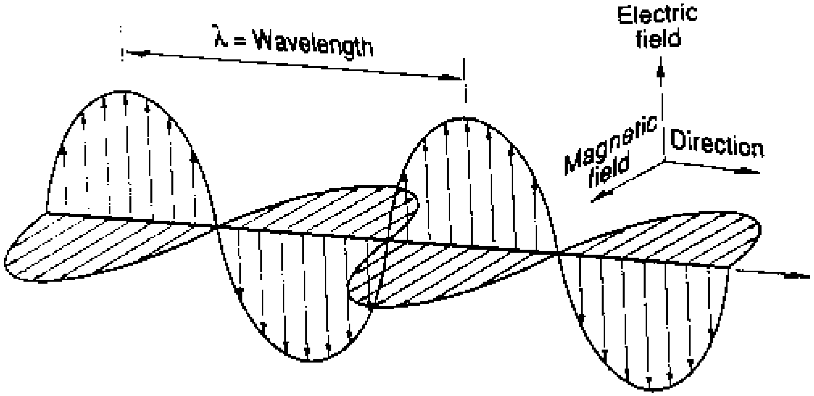
Tropea, Yarin, & Foss, "Springer Handbook of Experimental Fluid Mechanics," Part B Ch 6

The nature of light

- *Classical electromagnetic theory: light is radiation that propagates through vacuum in free space in the form of electromagnetic waves, both oscillating transversely to the direction of wave propagation and normal to each other.*

$$E_y(x,t) = E_{y0} \sin 2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)$$

$$B_Z(x,t) = B_{z0} \sin 2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)$$

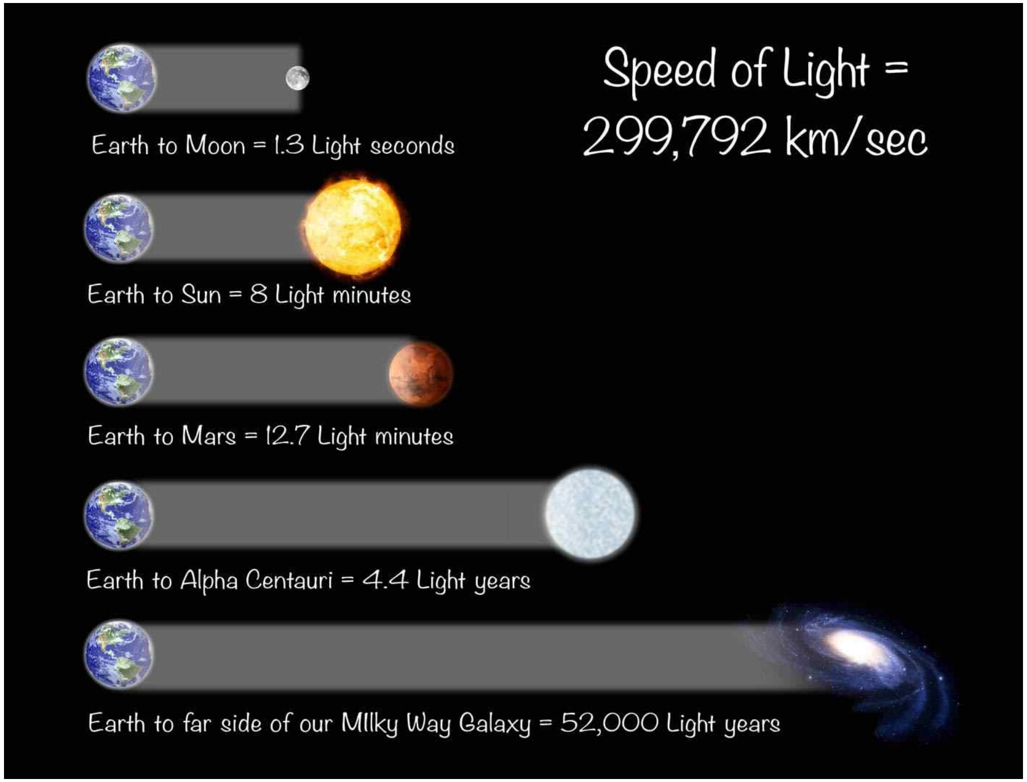


- ***λ :** **is wavelength***
- ***T :** **is the period of the oscillation***
- ***f:** **The reciprocal of the period,***

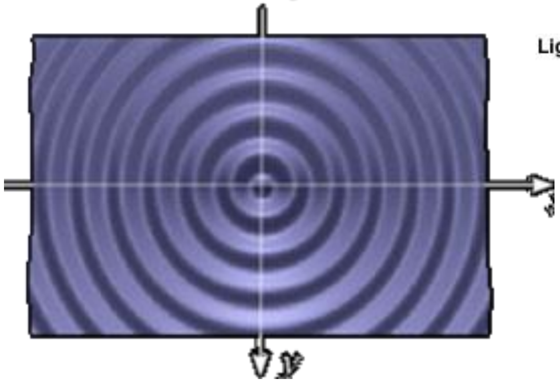
  is called frequency, f =1/T

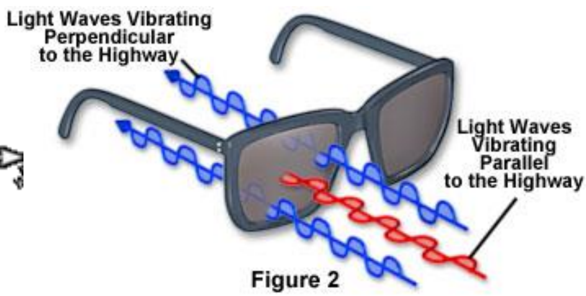
The nature of light-1

- *Light propagation velocity, $V = f\lambda$*
- *Light propagation velocity in Vacuum,*
  $C = 2.998\times10^{8}$ m/s
- *Wave front: the locus of all points along the different paths that have the same phase.*
- *If all the wave fronts are plane, then, the light is considered to be a plane wave.*
- *If all the wave fronts are spherical or cylindrical, then, the light is considered to be a spherical or cylindrical wave.*
- *Light propagation is associated with electric and magnetic fields.*
- *The polarization is associate with the orientation of the plane of the plane of oscillation of the electric field.*
- *Concepts of linearly polarized light, elliptically polarized light and circularly polarized light, unpolarized or randomly polarized light.*

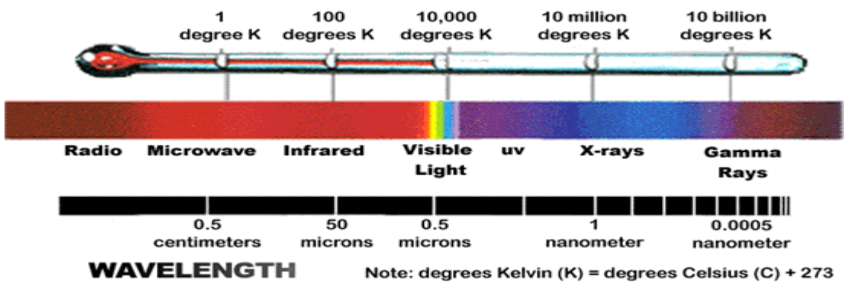


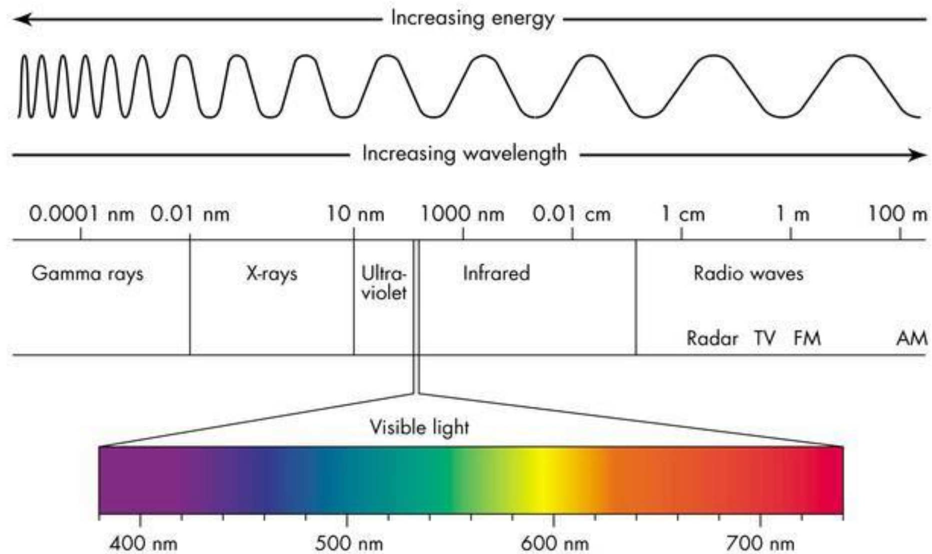
- ***wave fronts***
- ***Light propagation***



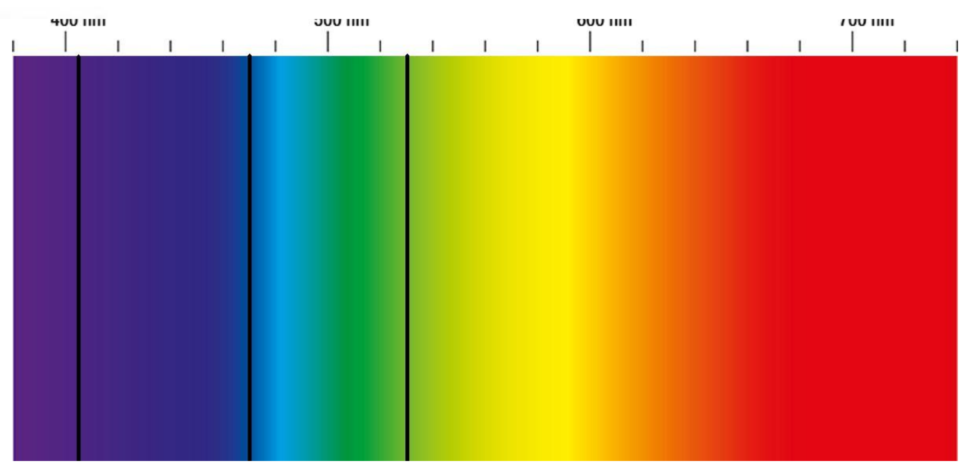


The nature of light -2



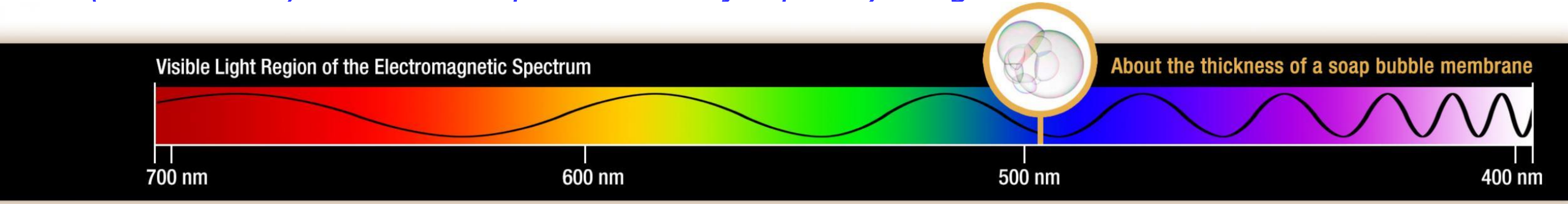


RADIATION TYPE	WAVELENGTH RANGE
Cosmic rays	$\lambda < 10^{-4}$ nm
Gamma rays	10^{-4} nm $< \lambda < 10^{-1}$ nm
X-rays	10^{-2} nm $< \lambda < 10^{2}$ nm
Disinfecting radiation	10 nm $< \lambda <$ 380 nm
Visible light	380 nm $< \lambda <$ 750 nm
Space heating	750 nm $< \lambda < 10^{7}$ nm
Microwaves	10^{6} nm $< \lambda < 10^{9}$ nm
Radar	10^{7} nm $< \lambda < 10^{9}$ nm
Radio and Television	10^{8} nm $< \lambda < 10^{13}$ nm
Electrical power waves	10^{14} nm $< \lambda < 10^{17}$ nm

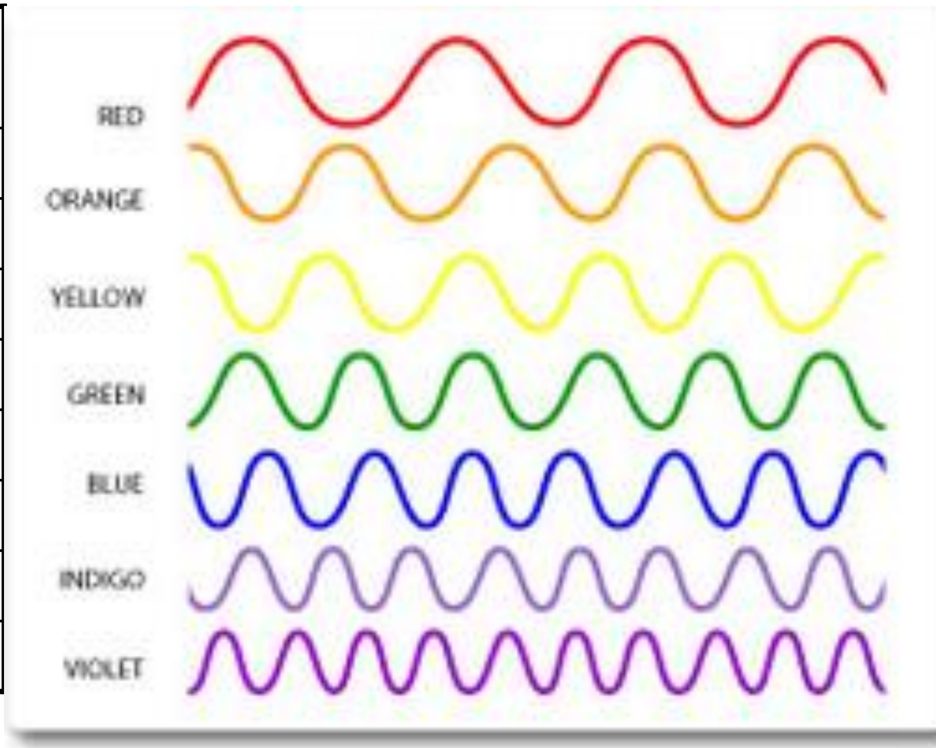


Visible light

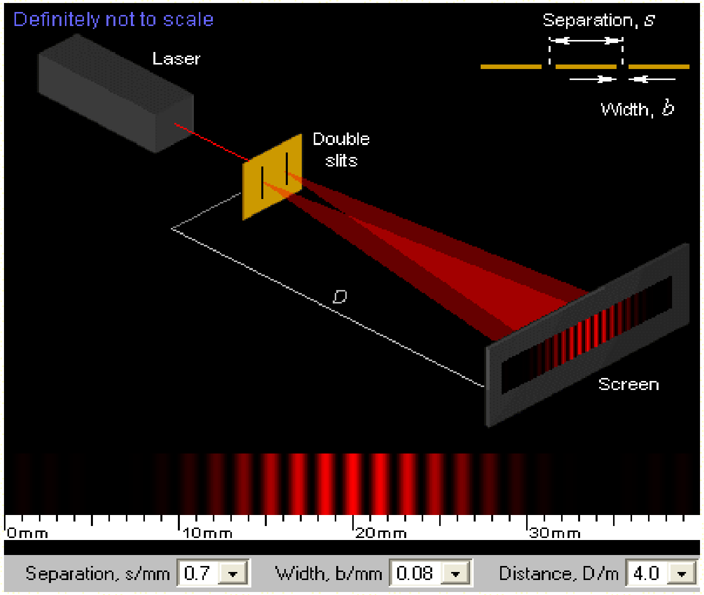
- *The colors: visible light consists of radiation with wavelength in the range of 380~750nm (1nm=10^{-9}m) which corresponds to the frequency range between 4.0×10^{15} to 7.9×10^{15} Hz.*

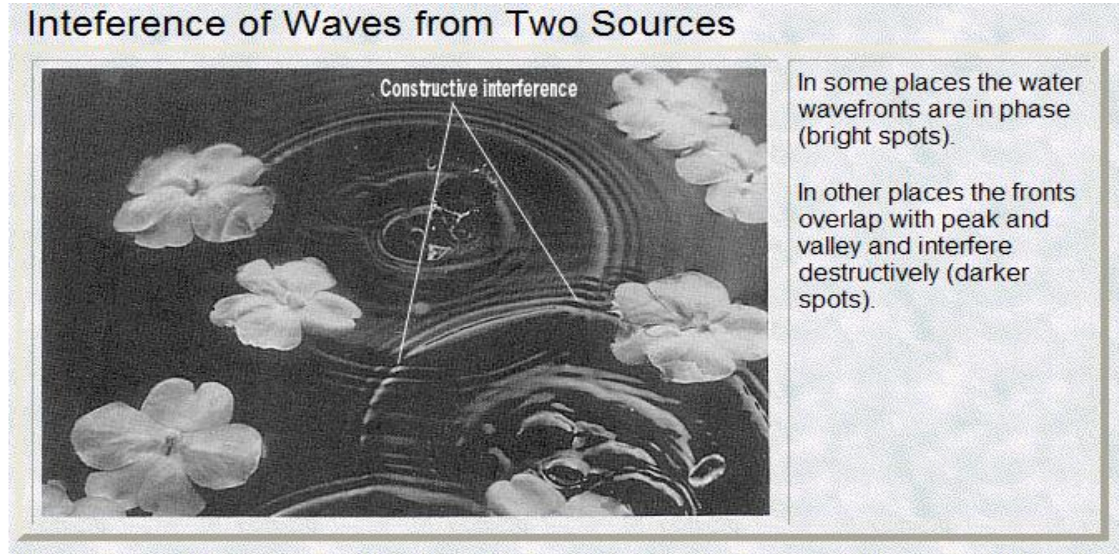


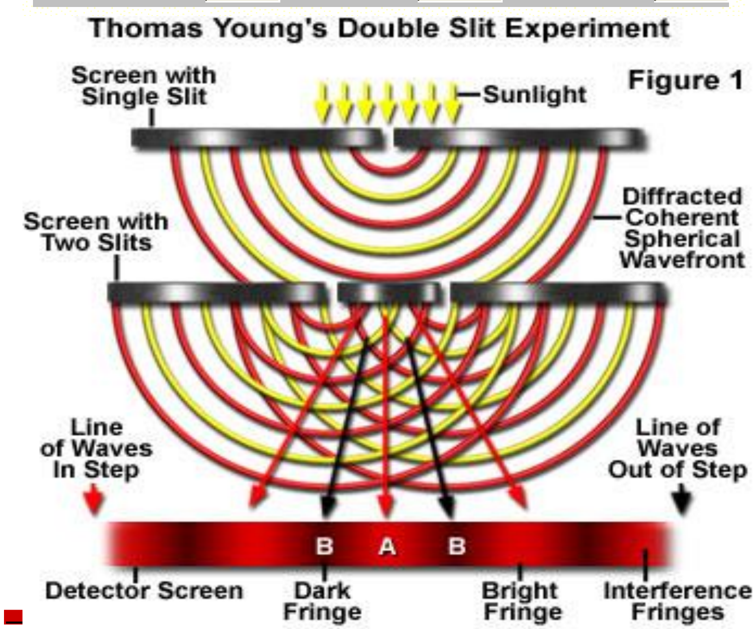
COLOR	WAVELENGTH RANGE
Ultraviolet (UV)	0.85 nm < λ < 380 nm
Violet	380 nm < λ < 424 nm
Blue	424 nm < λ < 491 nm
Green	491 nm < λ < 575 nm
Yellow	575 nm < λ < 585 nm
Orange	585 nm < λ < 647 nm
Red	647 nm < λ < 750 nm
infrared	750 nm < λ < 1000 nm

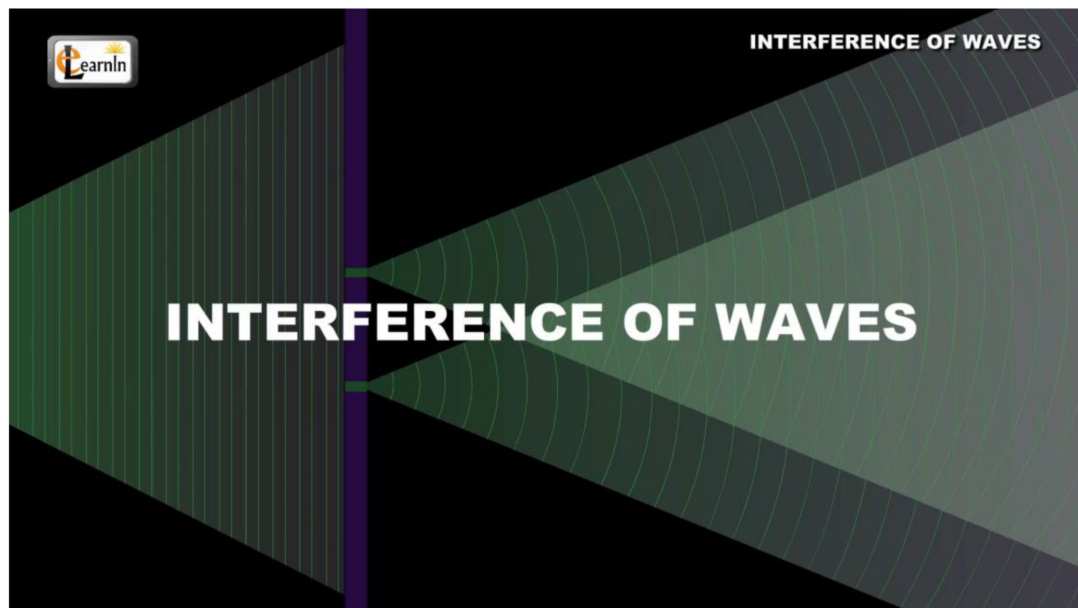


Light as a wave - Interference of light waves





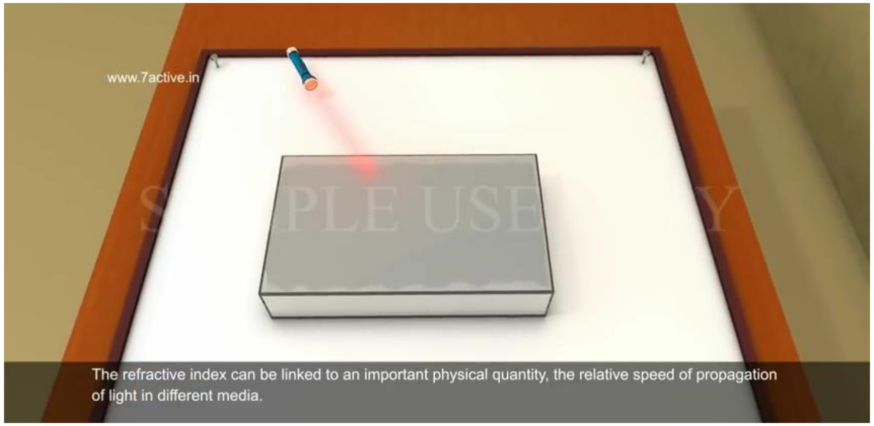




Light propagation through media

- ***Refractive index**:*

$$n = c / v = \frac{\lambda_0}{\lambda} > 1$$



Index of refraction of a material generally increasing slightly with decreasing wavelength of the light. Such phenomena is called dispersion.

$$n = \sqrt{\frac{1 + 2K_L \rho}{1 - K_L \rho}}$$

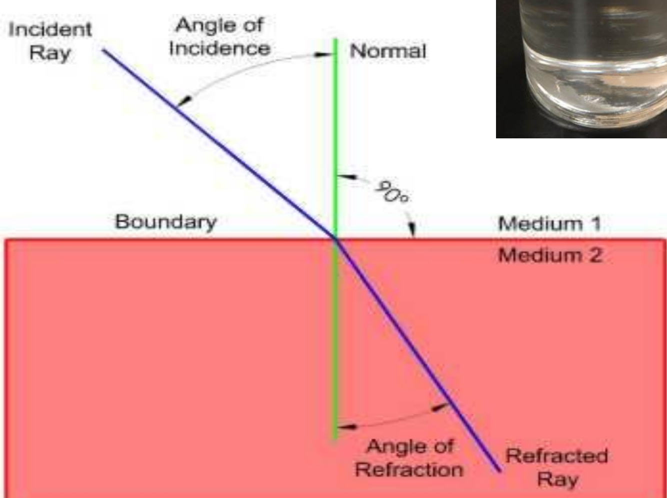
Gas	n	Liquid	n	Solid	n
Air	1.00029	Water	1.333	Fused quartz	1.46
He	1.00036	Ethyl alcohol	1.361	Pyrex glass	1.47
CO_2	1.00045	Turpentine	1.472	Crown glass	1.52
H_2	1.00013	Benzene	1.501	Flint glass	1.57~1.89
				Plexiglas	1.51
				Lexan	1.58
				Polystyrene	1.59
	589nm			sapphire	1.77
				zircon	1.92
				Diamond	2.42

Light propagation through media

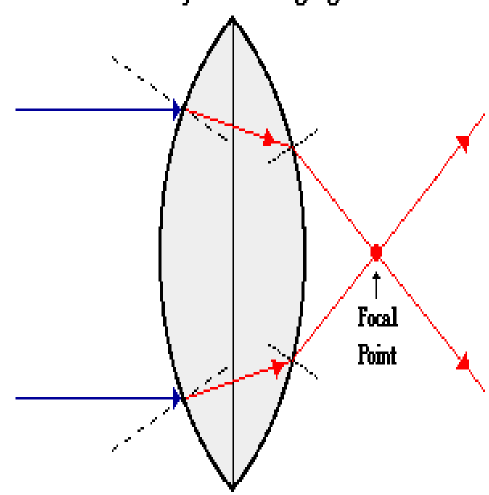
- ***Refraction:***
  - *When light propagates through a homogenous medium, its path would be straight, whereas, if the medium is non-homogeneous or if the light across from one medium to another, the path may change direction gradually or abruptly. The change of light propagation direction is called refraction.*

$$n = c/v = \frac{\lambda_0}{\lambda} > 1 \qquad \frac{\sin\varphi_1}{\sin\varphi_2} = \frac{n_2}{n_1}$$

  - *Optically denser medium ($n_1<n_2$)*
  - *Snell's Law:*

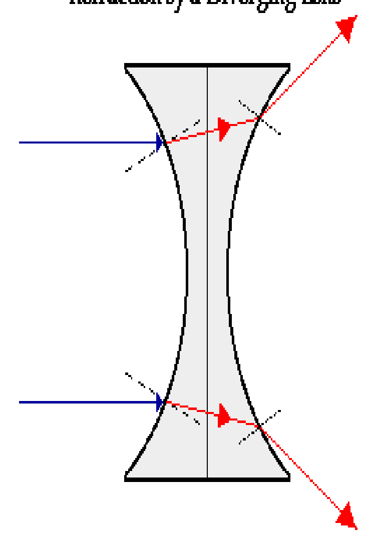


Refraction by a Converging Lens



Incident rays which travel parallel to the principal axis will refract through the lens and converge to a point.

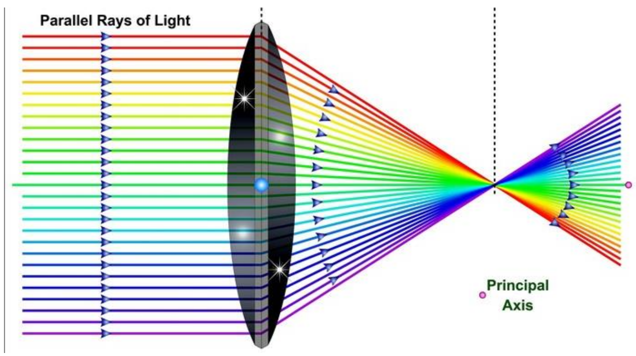
Refraction by a Diverging Lens

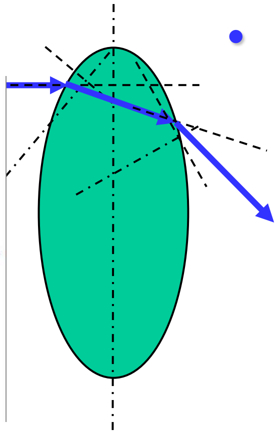


Incident rays traveling parallel to the principal axis will refract through the lens and diverge, never intersecting

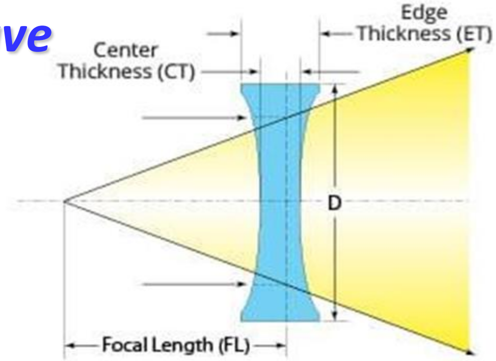
Light propagate through media

- *Convex lens*

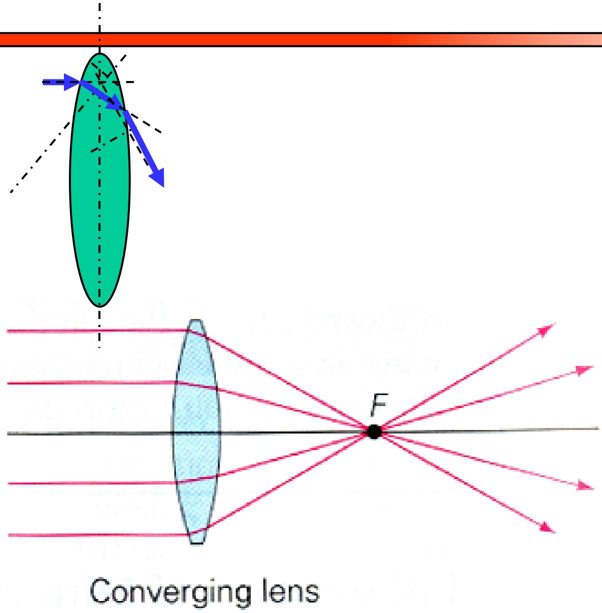


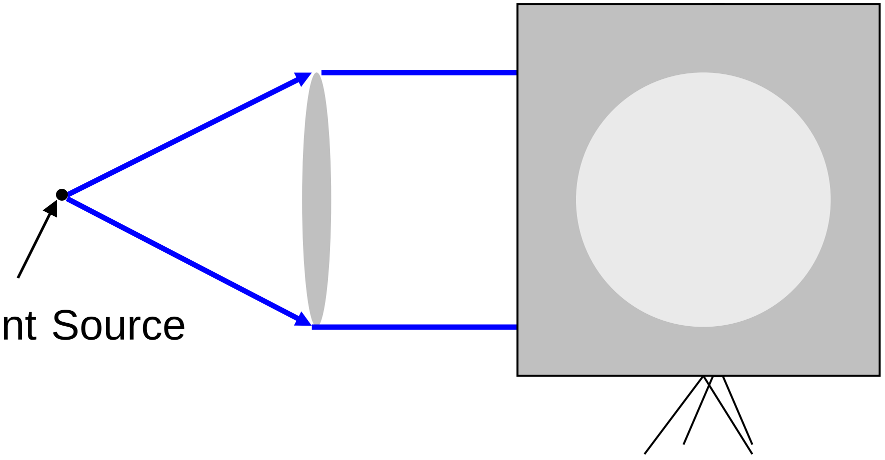


- *Concave lens*

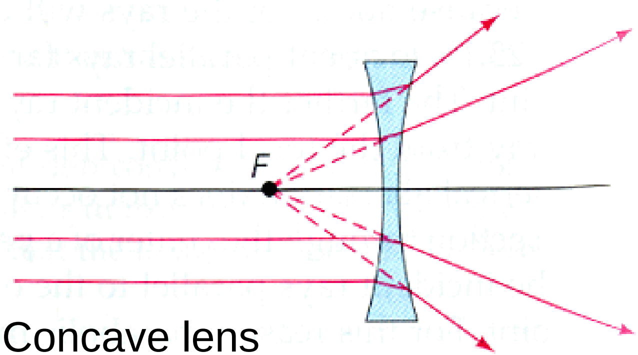


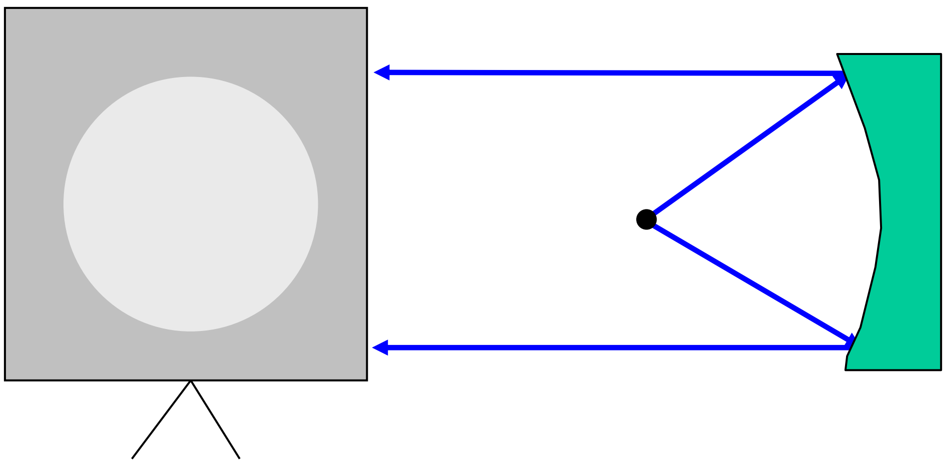
Lenses





Convex lens





Concave lens

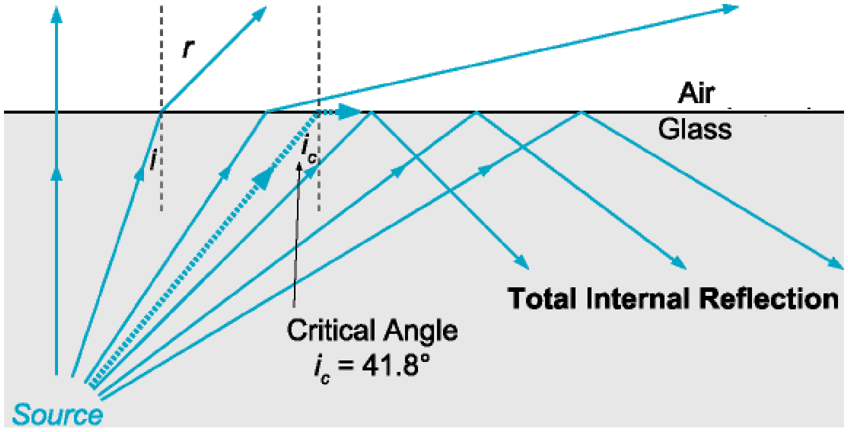
Light propagation through media

- *Total refraction*

$$\frac{\sin\varphi_1}{\sin\varphi_2} = \frac{n_2}{n_1}$$

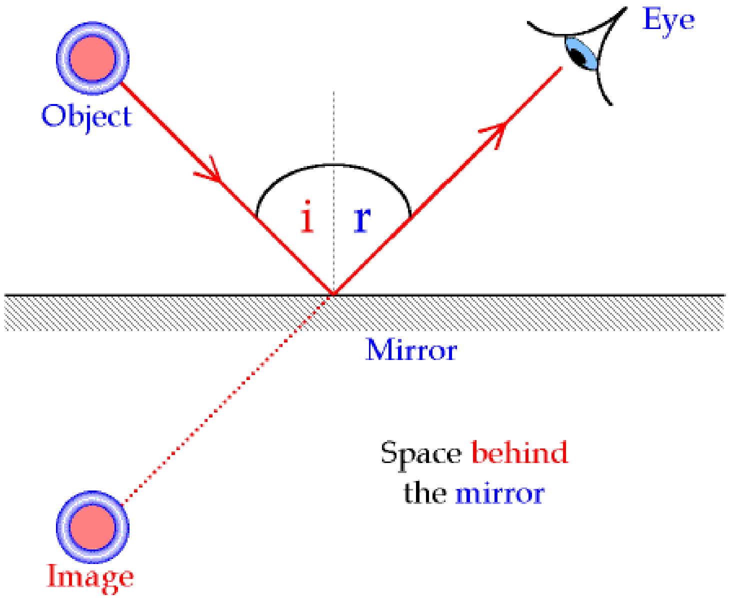
$$n_1 > n_2 \Rightarrow \varphi_2 > \varphi_1$$

$$\varphi_{2\max} > \pi/2 \Rightarrow \varphi_{1cri} = \sin^{-1}(n_2/n_1)$$



Refraction and total internal reflection.

- *Reflection*

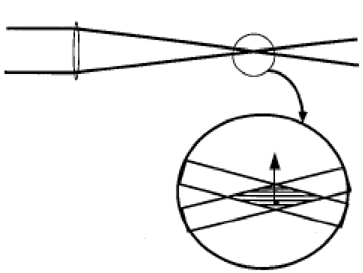


Light propagation through media

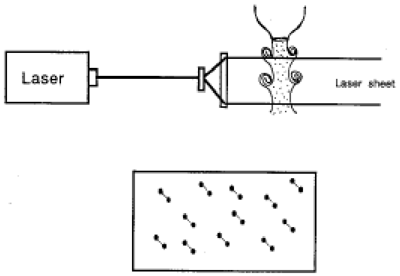
How does refractive-index-matching help?

- Optical techniques avoid disturbing the flow to be measured
- Typical approaches are LDV, PIV, PTV, flow visualization, PLIF, etc.

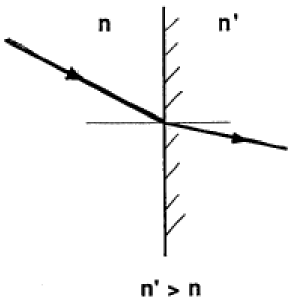
Laser Doppler Velocimetry



Particle Image Velocimetry

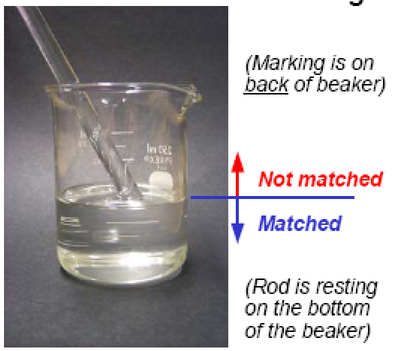


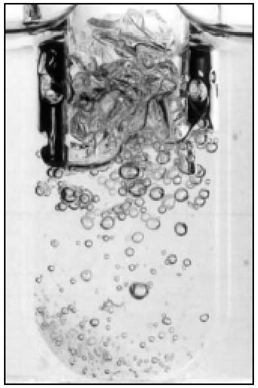
Snell's Law



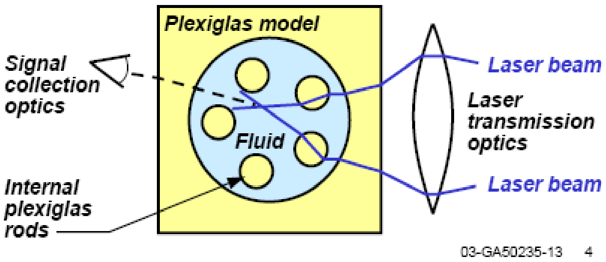
- Unless the refractive indices are matched, the view may be distorted or impossible even with "transparent" materials and position measurements may be incorrect

Example of application of refractive-index-matching

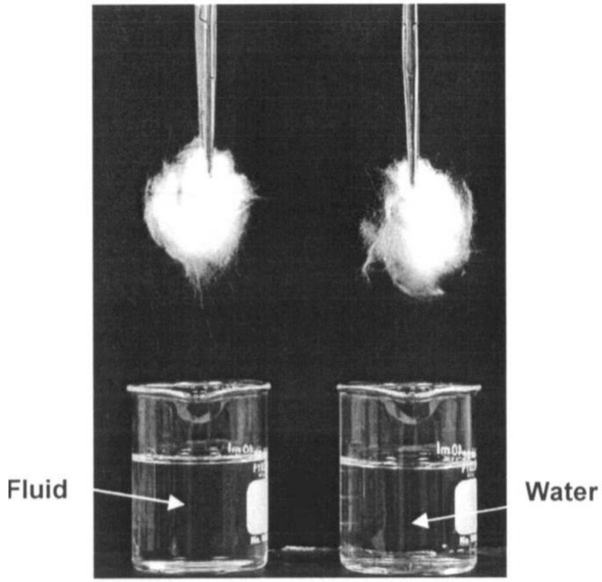


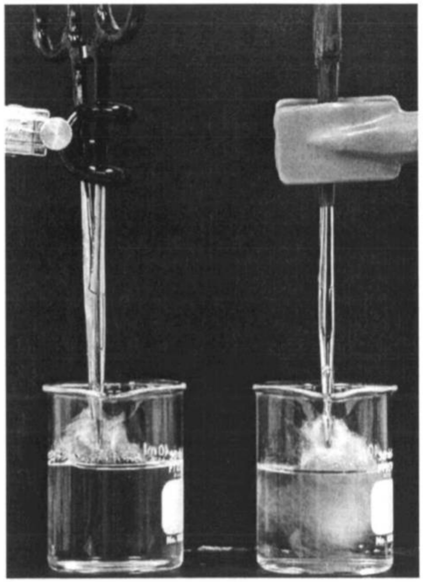


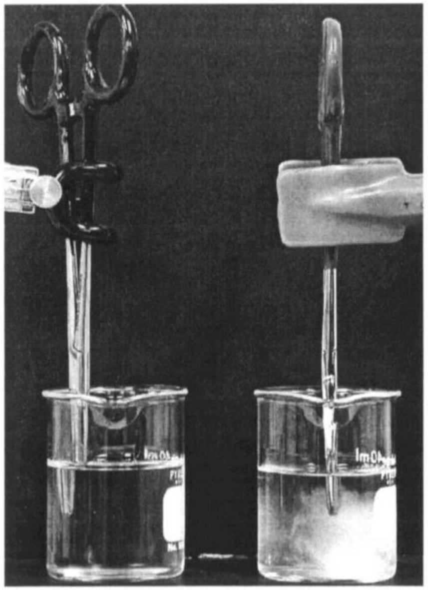
Refractive index not matched

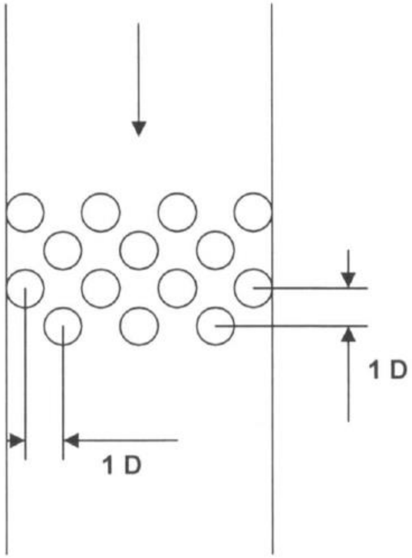


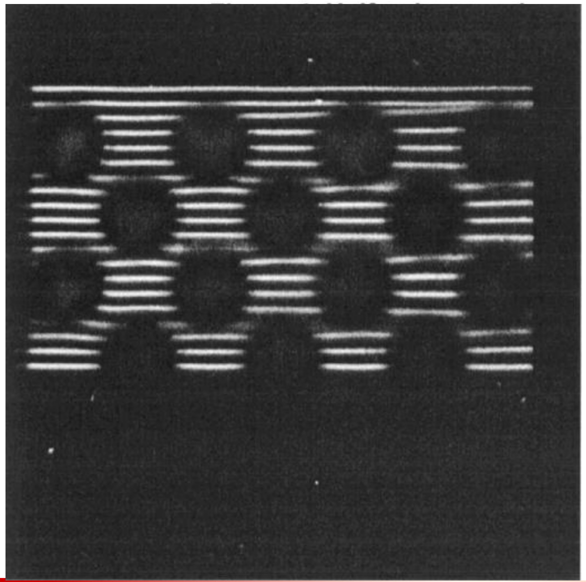
The Optical Index of Refection Matching Approach

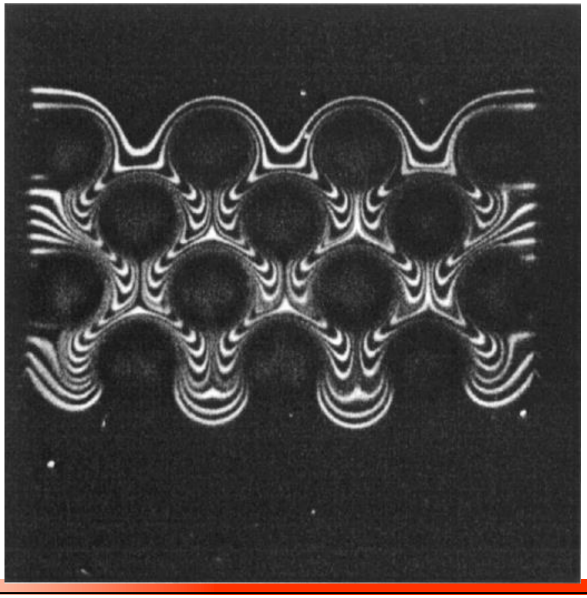








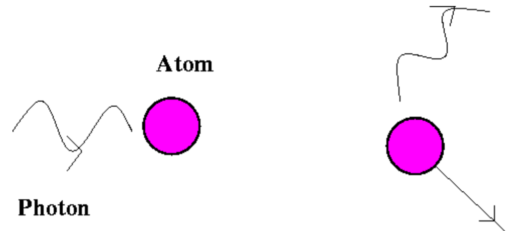




The nature of light – as photons

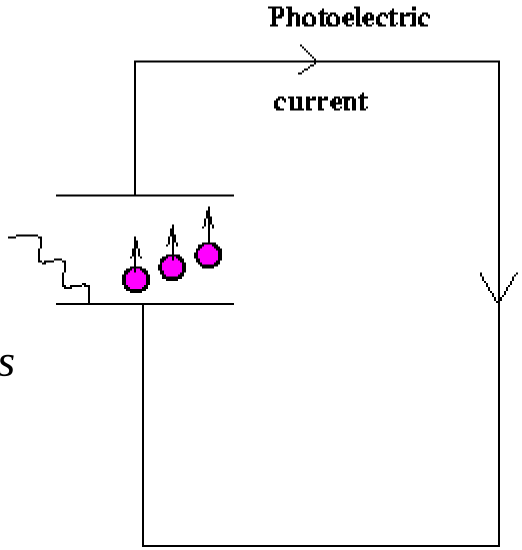
Photon scattering:

- *one finds experimentally that the frequency of the scattered wave is changed, which does not come out of a wave picture of light. However, when the light is viewed as a photon with energy proportional to the associated light wave, excellent agreement with experiment is found.*



$$\varepsilon = h\nu$$

$$Planck\,const = 6.624 \times 10^{-34}\,Js$$

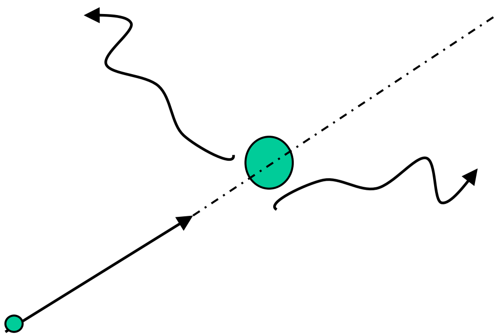


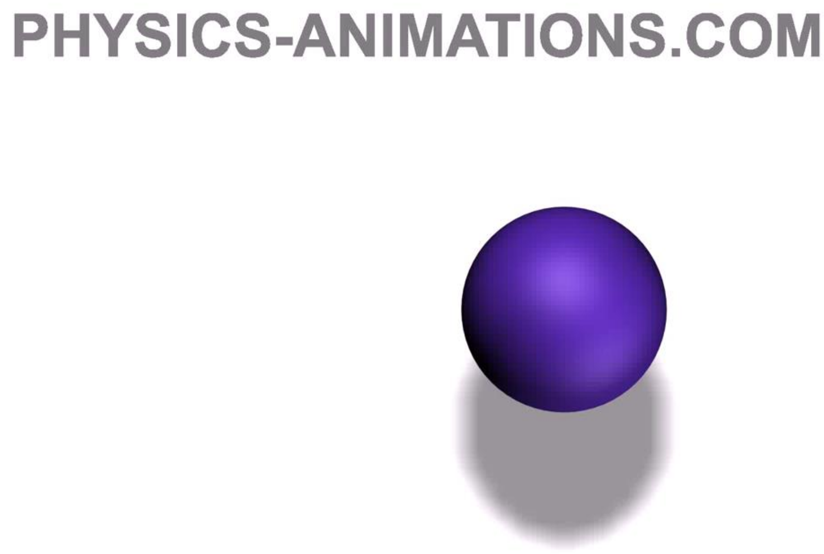
The photoelectric effect:

- *When light shines on a metal plate, electrons are ejected. These electrons are accelerated to a nearby plate by an external potential difference, and a photoelectric current is established, as below*
- *The photons hit an electron in the metal, giving up energy. If photon energy is sufficient to free the electron, it is accelerated towards the other side; hence, a flow of charges (current).*
- *The photoelectric current depends critically on the frequency of the light. This is a feature of the energy that the electrons gain when struck by the light.*
- ***The explanation was first given by Einstein and won him the Nobel Prize.***

Light Scattering

- *Scattering*
  - *Scattering is a general physical process whereby some forms of radiation, such as light, are forced to deviate from a straight trajectory by one or more localized non-uniformities in the medium through which it passes.*
- *Elastic Scattering*
  - *Excited electron or atoms emits a photon with exact the same frequency as the incident one.*
- *Inelastic scattering*
  - *Excited electron or atoms emits a photon with a frequency different from the incident one.*





Elastic scattering

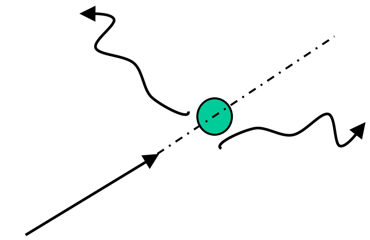
Rayleigh Scattering

- *Light scattering from particles that are smaller than 1/15 of the incident light wavelength (d< λ/15).*
- *Efficiency of the scattering from a particle is expressed in terms of scattering cross section.*

$$\sigma_R = \sigma_T \left(\frac{\lambda_0}{\lambda}\right)^2$$

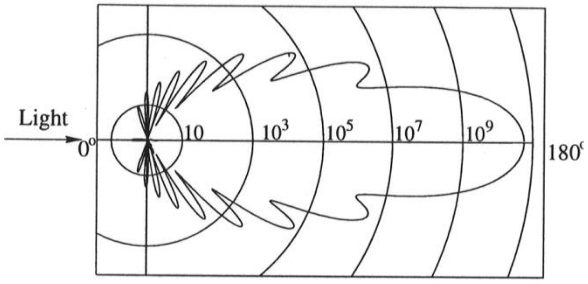
$$\sigma_T = 6.65 \times 10^{-29} m^2$$

λ_0 is the charateristic wavelength of the atom.

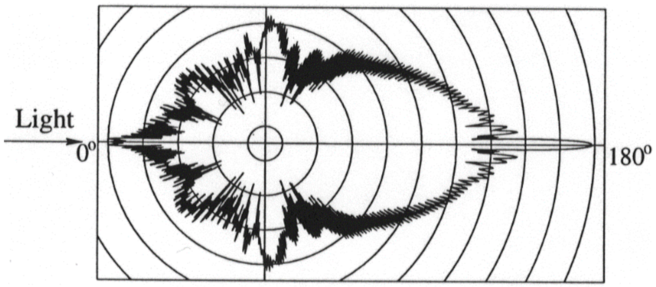


Mie Scattering

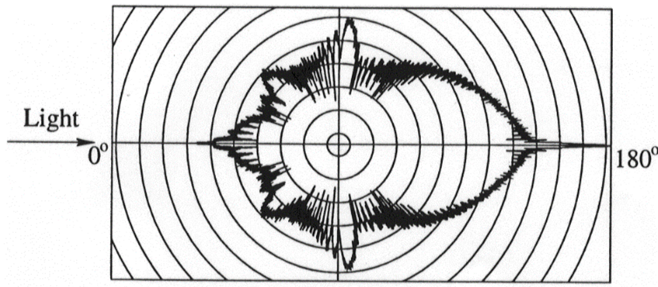
- *Light scattering from a particles with its size close on bigger than the incident light wavelength (d > λ).*
- *Conservation of polarization direction*
- *Angle dependent*
  - *Forward scattering*
  - *Back scattering*



(a). d=1μm



(b). d=10μm



(c). d=30μm

Inelastic Scattering

Raman Scattering

- *Inelastic scattering from molecules.*
- *Chance to occur is about 10^{-5} ~ 10^{-2} of times lower than the Rayleigh scattering*
- *Scattering cross section is several orders smaller than the Rayleigh scattering*
- *Stoke transition : the energy of the emitted photon is higher than the absorbed photo.*
- *Anti-stoke transition: the energy of the emitted photon is lower than the absorbed photo.*
- *Time between the absorption and emission: 10^{-14} s.*
- *Anti-stokes line will be stronger when the temperature is low.*

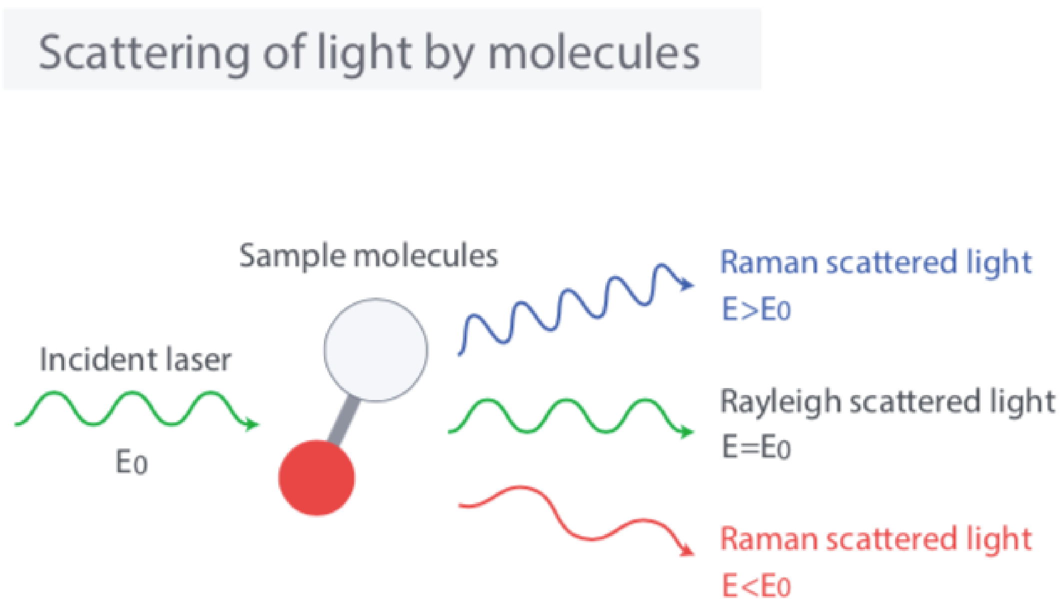


Table 5.5. Wavelengths of Raman-scattered radiation for some common molecules in air at standard atmospheric pressure and a temperature of 295 K; excitation was provided by a ruby laser

Molecule	Anti-Stokes line (nm)	Stokes line (nm)
Incident light	694.30 (Rayleigh line)	
CO_2	638.23	761.17
CO_2	637.92	762.23
CO_2	633.25	768.37
CO_2	632.42	769.61
O_2	626.57	778.44
O_2^+	615.50	796.23
NO	614.26	798.31
CO	604.34	815.73
N_2^+	603.19	817.82
N_2	597.57	828.39
CH_4	577.45	870.46
H_2	538.67	976.41

Fluorescence and phosphorescence

– Rayleigh and Raman scattering occurs essentially instantaneously. Not allowing other energy conversion phenomena to occur.

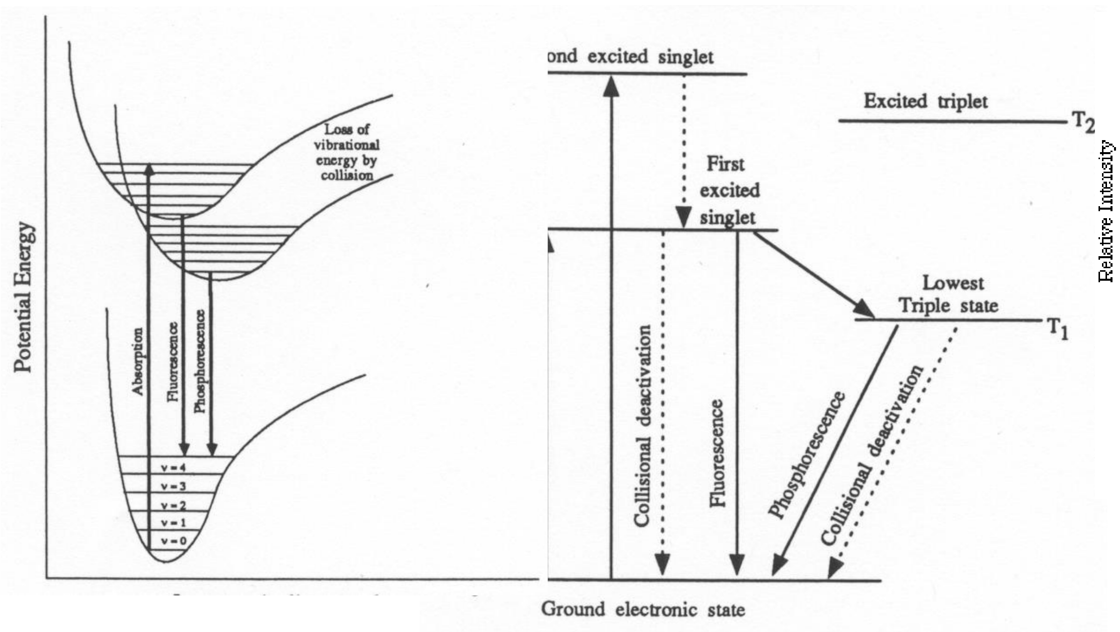
Fluorescence and phosphorescence

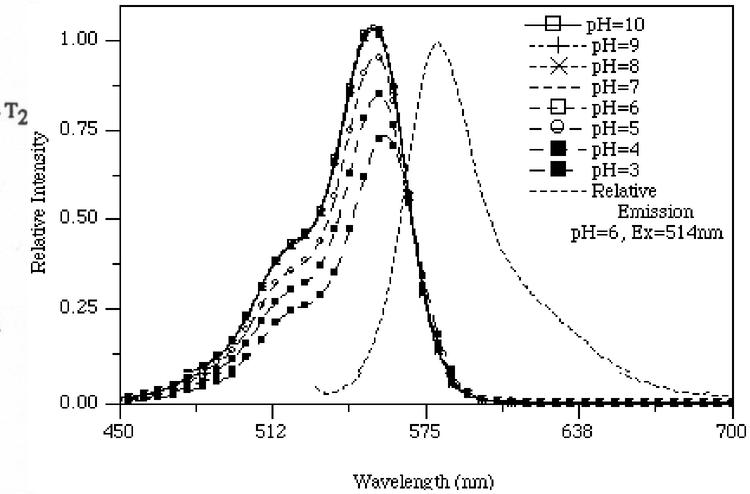
– Photoluminescence with time delay

Fluorescence

– Emission when the excited from singlet state to ground,

– lifetime is about $10^{-10} \sim 10^{-5}$ s.



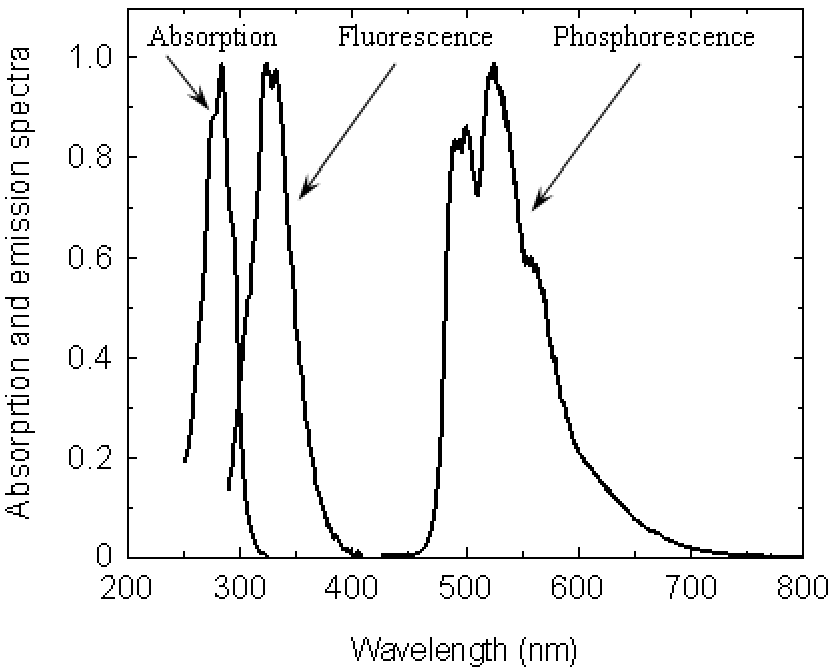


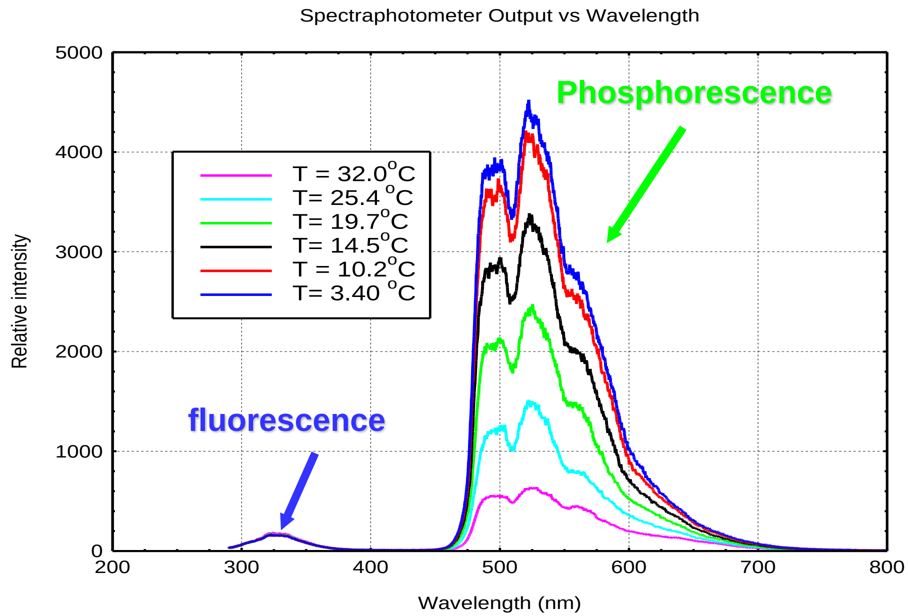
Rhodamine B

Fluorescence and phosphorescence

Phosphorescence

- Emission when the excited atom or molecule from triplet state to ground,
- lifetime is about $10^{-4} \sim 10^{-5}$ s.



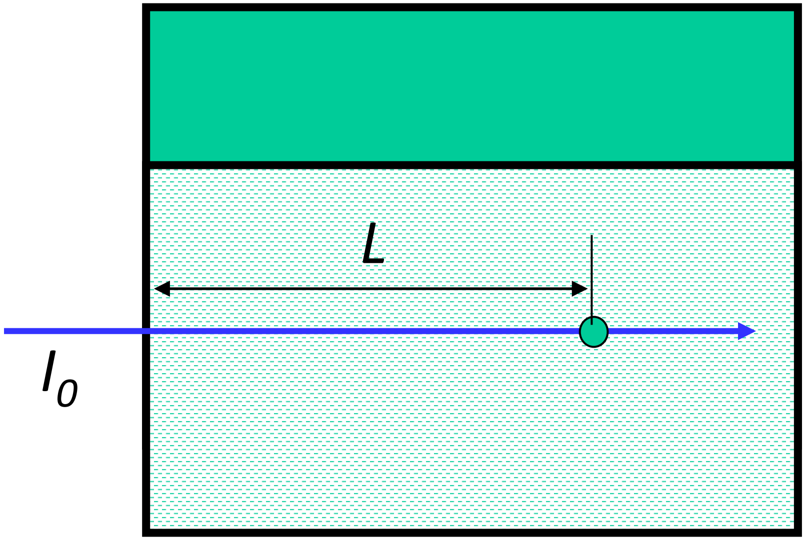


MTV chemical: 1-BrNp•Mβ-CD•ROH complex

Absorption

Light is transmitted through a material, it will be absorbed by the molecules of the material

Beer's law: $$I = I_0 \exp(-\alpha L)$$



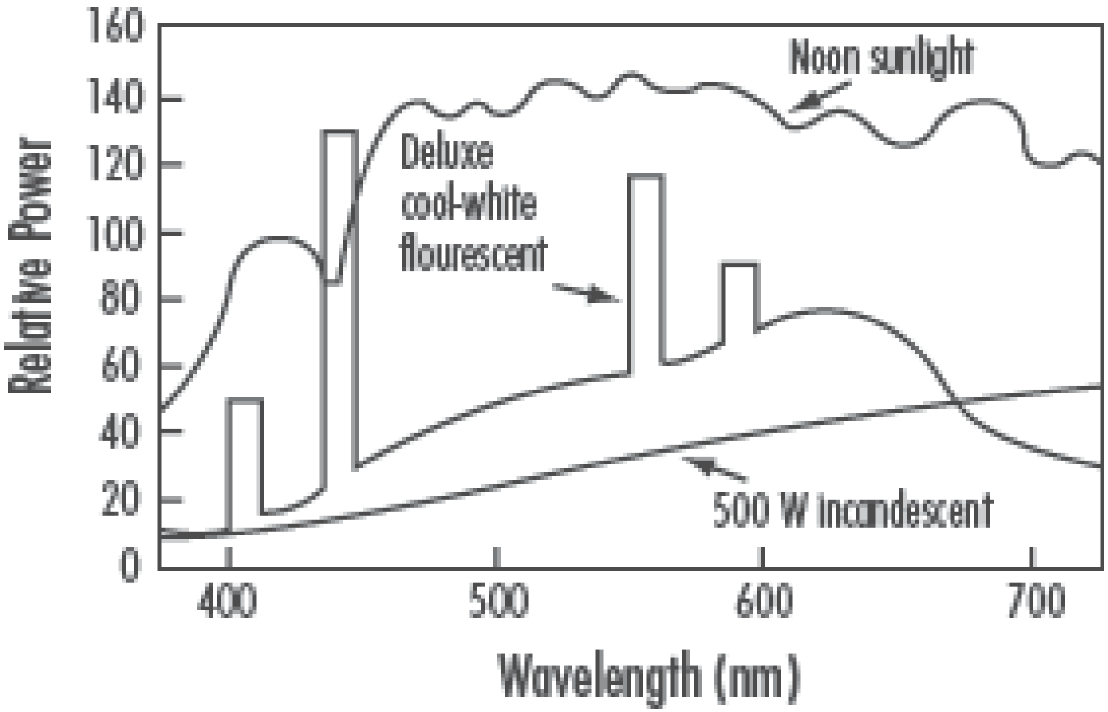
- ***α is the absorption or attenuation coefficient***
- ***Lc=1/α is called penetration depth.***
- ***When $L=L_c$, $I/I_0=1/e=37\%$, i.e., 63% energy was absorbed***
- ***Metals have very small Lc=1/α.***
  - ***Copper, Lc=0.6nm for 100 nm UV light***
  - ***Copper, Lc=6.0nm for 1000 nm infrared light.***
  - ***2nm copper plate as a low pass filter.***

Illumination

Light sources:

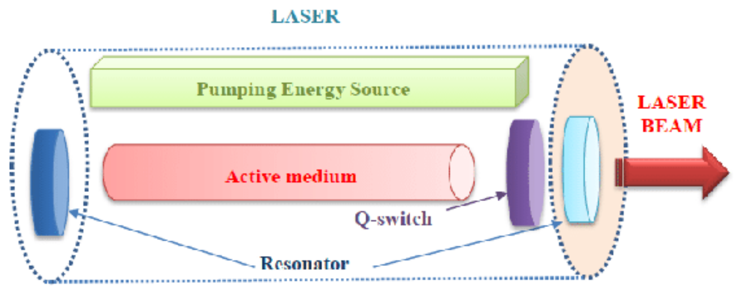
- ***Thermal source:***
  - ***Lamps: Continuous wave (CW)***
  - ***Flash lamps (Pulsed)***
  - ***Arc lamps***

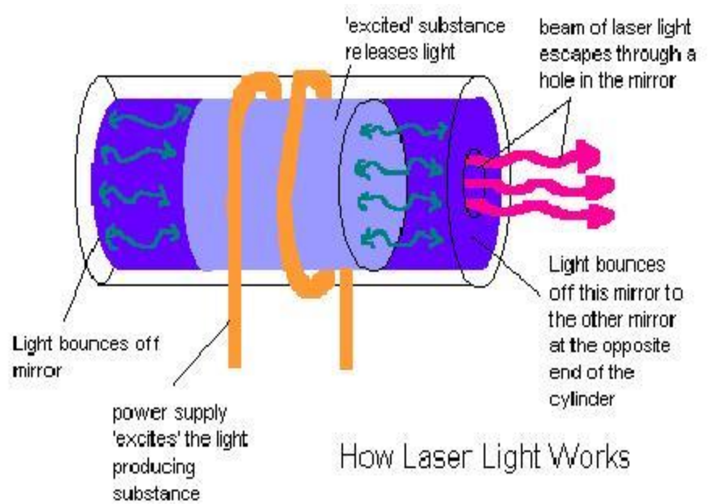
- ***Laser sources***
  - ***Continuous wave (CW)***
  - ***Pulsed laser***
  - ***Singe wavelength***



Laser

- *Laser: Light Amplification by Stimulated Emission of Radiation (LASER)*
- *How a laser works:*
  - *Radiation energy is produced by an activated medium(can be gas, crystal or semiconductor or liquid solution).*
  - *The medium consists of particles (atom, ions or molecules).*
  - *When a photo, having energy hv, approaching the particles, the photo may be absorbed cause an electron or atoms to be raised temporarily to high-energy level.*
  - *When the excited electron or molecule to return ground level, spontaneous emission or stimulated emission would take place.*

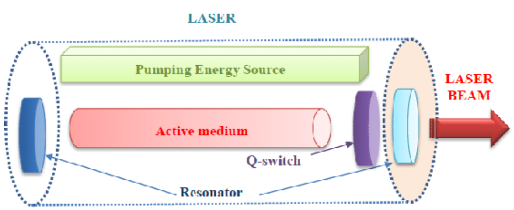


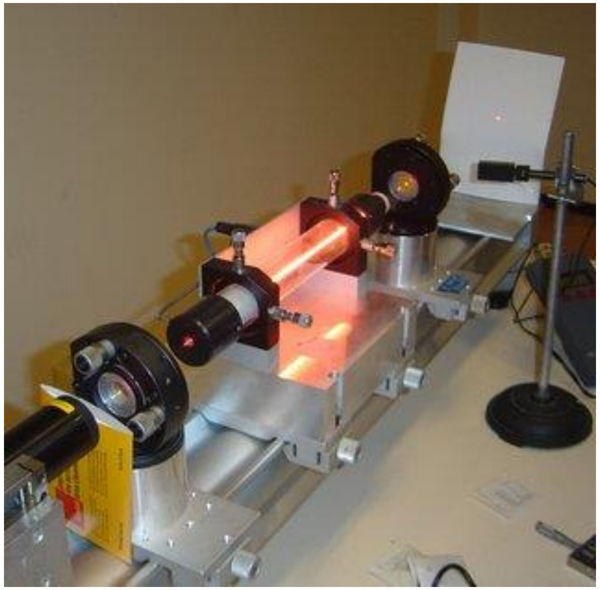


Commonly used Lasers

–*Helium-neon (He-Ne) laser*

- *Active medium is helium neon atoms*
- *Continuous wave laser*
- *Power 0.3 ~15 mW*
- *λ =633nm (red)*





–*Argon-ion (Ar-ion) laser*

- *Active medium is argon atoms maintained at the ion state.*
- *Continuous wave laser*
- *Power level: 100 mW ~10 W*
- *Have seven wavelengths*
- *λ =488n (blue)*
- *λ =514.5nm (green)*
- *LDV application*
- *LIF in liquid flows*

Commonly used Lasers

– ***Nd-YAG laser***

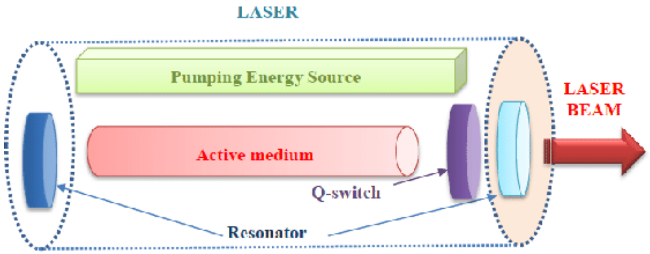
- *Solid-state laser*
- *Active medium: neodymium (Nd+3) as active medium incorporated as an impurity into a crystal of Yattium-Aluminium-Garnet (YAG) as a host*
- *Flash lamp is used as external source*
- *pulsed laser: 10 -400mJ/pulse or more*
- *Pulse duration: 100ps ~ 10ns*
- *Wavelenght of tube λ =1064nm (infrared)*
- *SHG: λ =532nm (green), THG: λ =355nm (UV), FHG: λ =266nm (deepUV)*
- *PIV, MTV, PLIF*
- *Repetition rate can be as high as 30 Hz.*

– ***Dye laser***

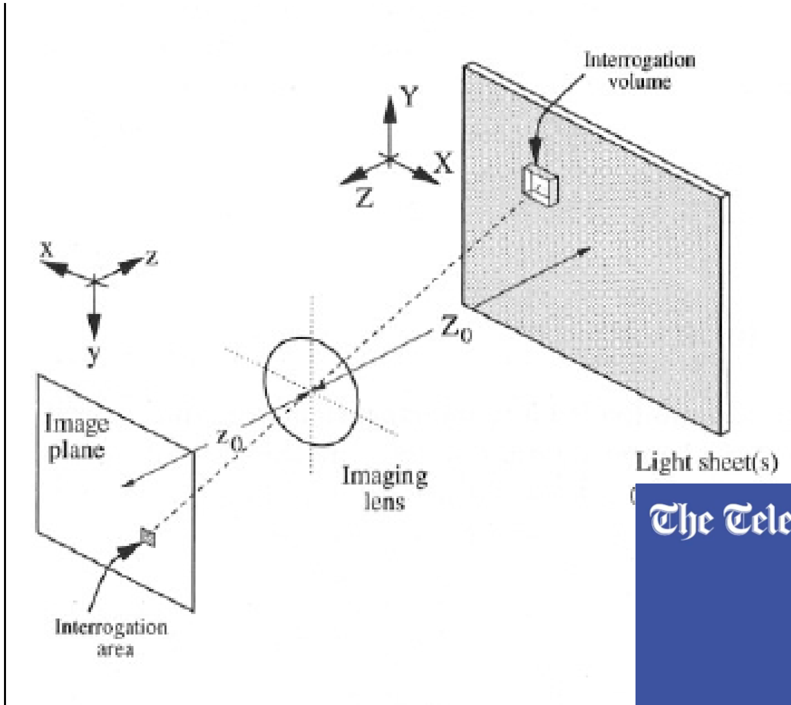
- *Active medium: complex multi-atomic organic molecules*
- *λ =200nm ~ 1500nm*

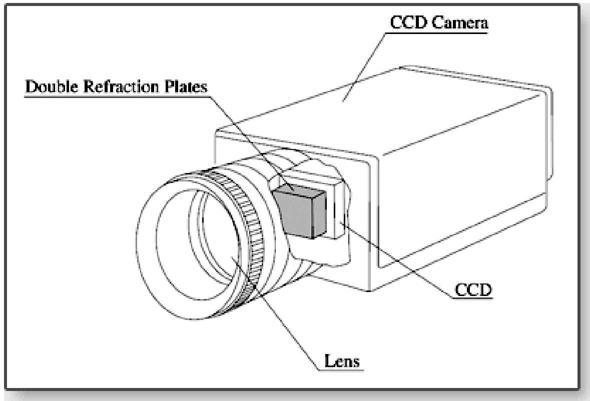
– ***Excimer laser***

- *Gas laser KrF and Xecl*
- *High-energy*
- *UV wavelength*
- *Pulsed laser*
- *high repetition frequency*



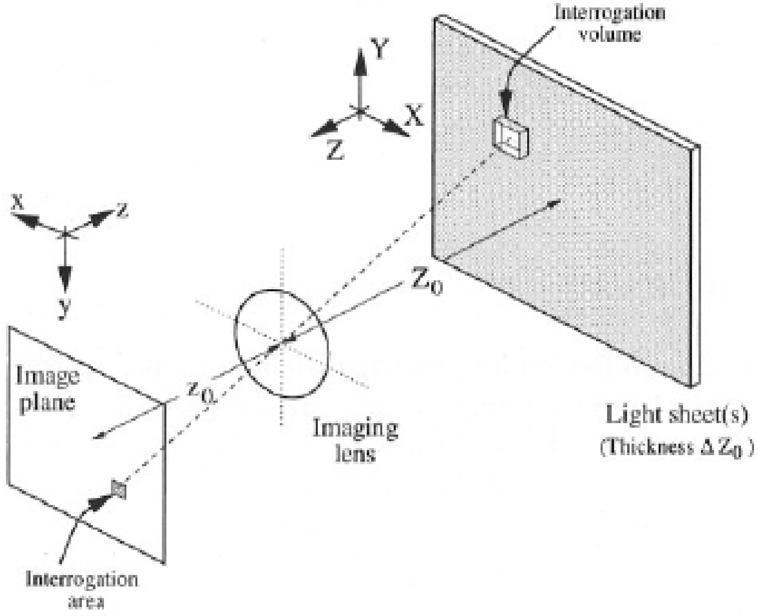
Light sensing and recording





The Telegraph

Lenses



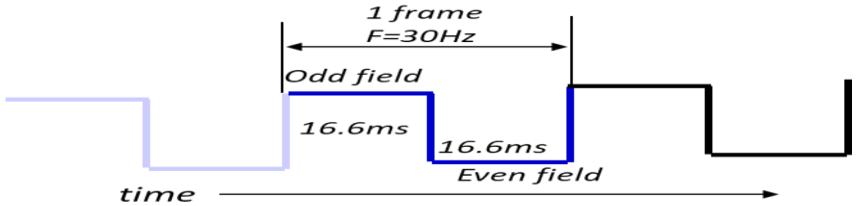
- Focal length: **f**
- **f/#** , "F-number": defined as the ratio of focal distance of the lens and its clear aperture diameter.
- Depth of focus ***H = 2 ·f/# · c · Z/f***

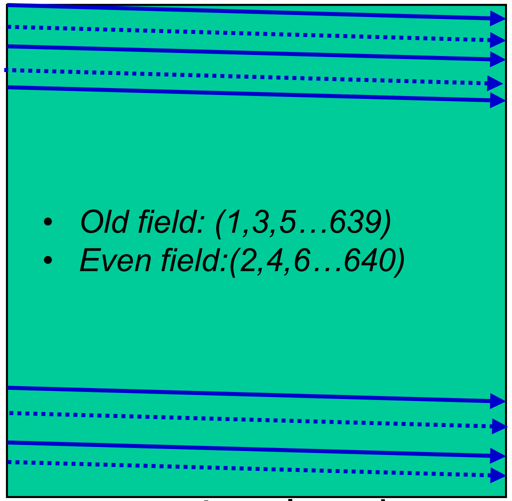
f2 F2.8	f4 f5.6 f8 f11	f16 f 22
wide aperture		small aperture
more light		less light
small number		larger number
		

Interlaced Cameras

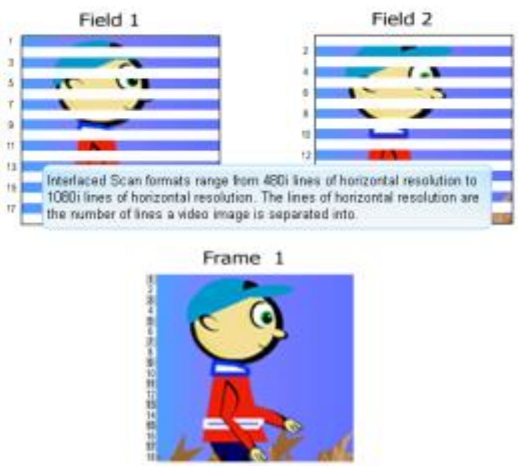
- *The fastest response time of human being for images is about* ***~ 15Hz***
- *Video format:*
  - *PAL (Phase Alternating Line) format with frame rate of f=25Hz (sometimes in 50Hz). Used by U.K., Germany, Spain, Portugal, Italy, China, India, most of Africa, and the Middle East*
  - *National Television Standards Committee (NTSC) with frame rate of f=30Hz. Used by U.S., Canada, Mexico, some parts of Central and South America, Japan, Taiwan, and Korea.*

  480 pixels by 640 pixels





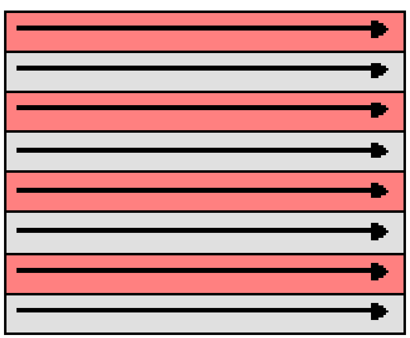
Interlaced camera



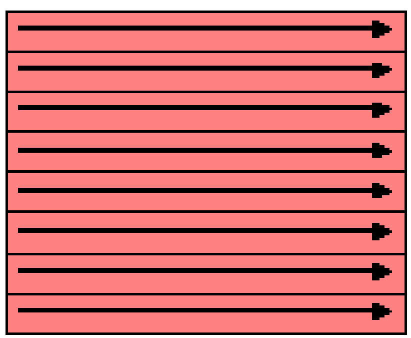
Interlaced camera vs. Progressive Scan Camera

Note: In these examples, the cameras have been using the same lens. The car has been driving at 20 km/h (15 mph) using cruise control.

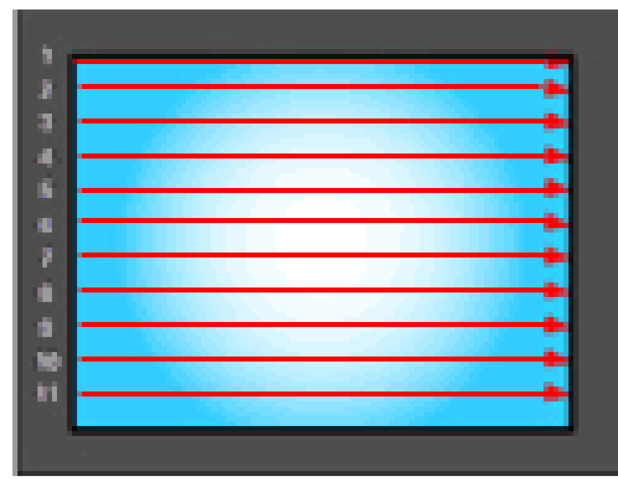
- *All image systems produce a clear image of the background*
- *Jagged edges from motion with interlaced scan*
- *Motion blur caused by the lack of resolution in the 2CIF sample*
- *Only progressive scan makes it possible to identify the driver*



Interlaced



Progressive Scan
(Non-interlaced)



One complete frame
using progressive scanning

Electronic shutter modes

- ***Rolling shutter:*** *The sensor is exposed line by line. Each of the pixels integrate light for the specified exposure time; however, not all pixels are exposing at the same time. The start time for each pixel's exposure is a function of sensor position. This mode is typical of large format sensors, such as digital SLR cameras.*

- ***Global shutter:*** *Each pixel integrates light for the specified exposure time simultaneously. This method is preferred for capturing highly dynamic events. This mode is typical of high-speed CMOS cameras which can operate at frame rates beyond 1 million frames per second.*

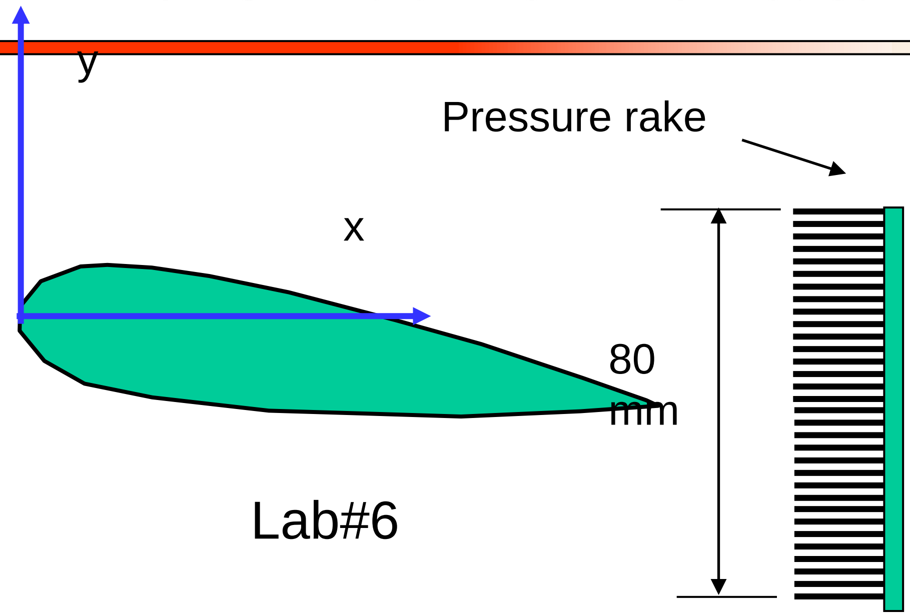
Rolling shutter
Point Grey Cameras

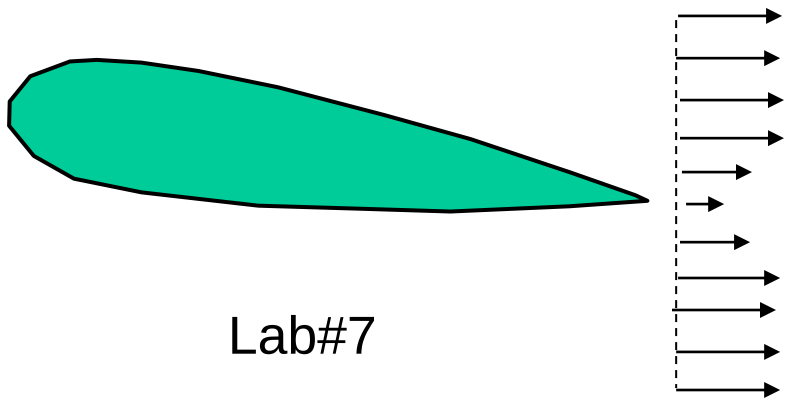
Gobal shutter
Point Grey Cameras

Mystery of flying rods

- *WT testing @ 13:30;*
- *High-speed Imaging @29:30; 33:00; 38:20*

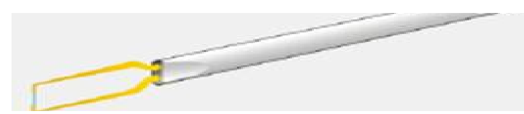
AerE344 Lab7: Hot wire measurements in the wake of an airfoil





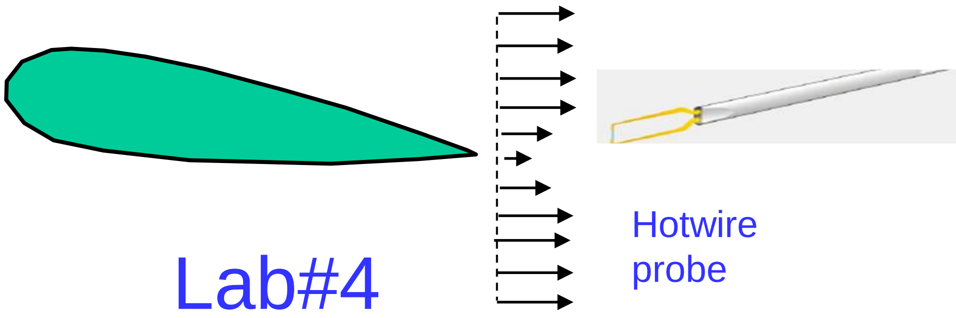
Test conditions:

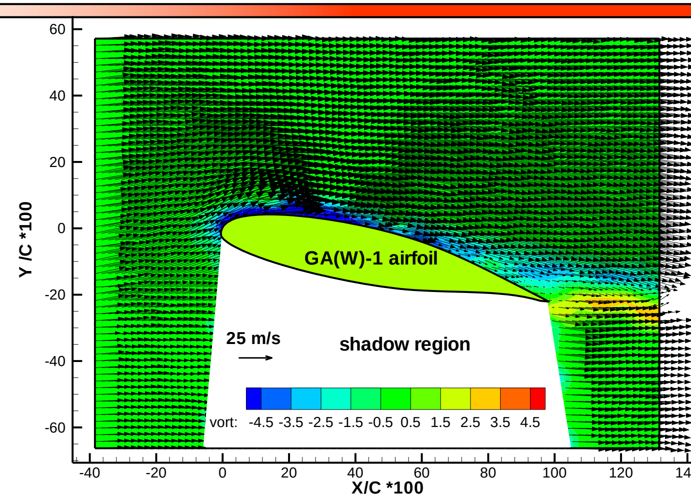
Velocity:	V=15 m/s
Angle of attack:	AOA=0, and 12 deg.
Data sampling rate:	f=5000Hz
Number of samples:	50,000 (10s in time)
No. of points:	20~25 points
Gap between points:	~0.2 inches

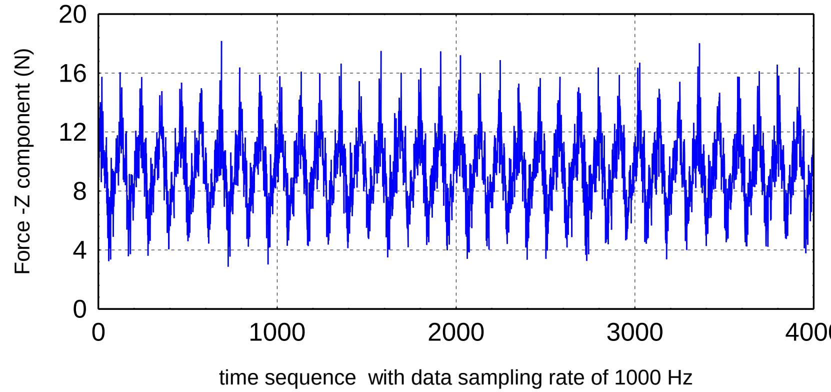


Hotwire probe

AerE344 Lab: Hot wire measurements in the wake of an airfoil







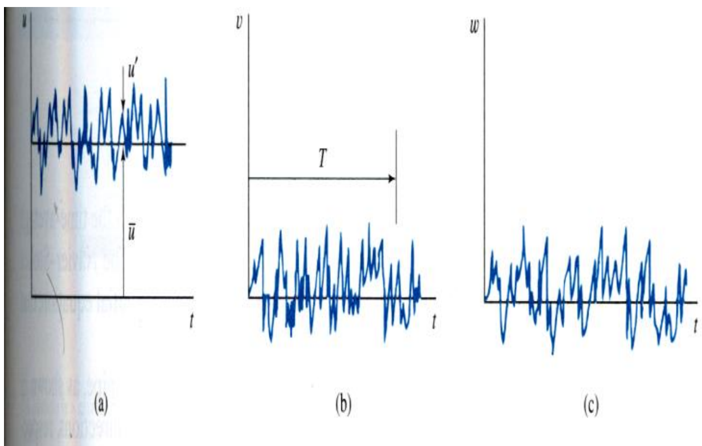
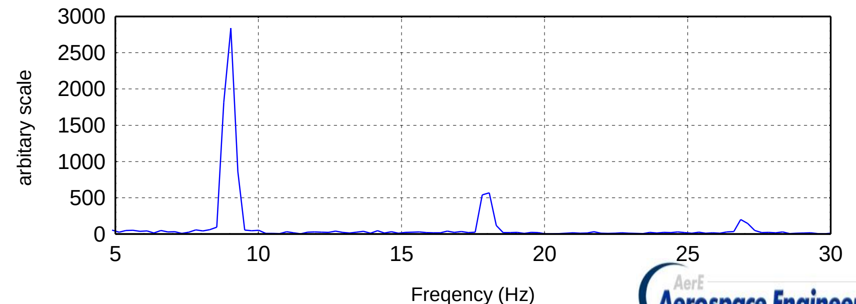
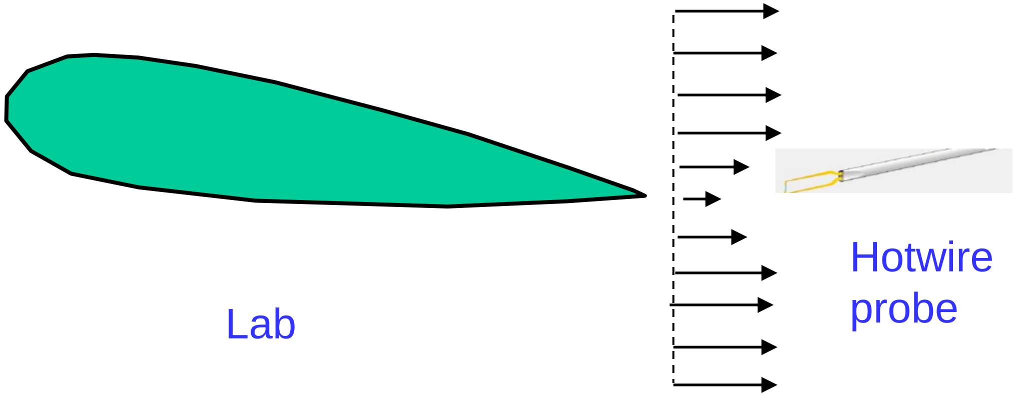


FIGURE 7.7 Velocity components in a turbulent pipe flow: (a) x-component velocity; (b) r-component velocity; (c) θ-component velocity.

FFT



AerE344 Lab: Hot wire measurements in the wake of an airfoil



Required data for the lab report:

1. Wake velocity profiles at AOA =0 and 12 deg
2. Wake turbulence intensity profiles at AOA =0 and 12 deg.
3. Estimated drag coefficients at AOA=0, and 12 deg.
4. FFT transformation to find vortex shedding frequency in the wake of the airfoil
5. Discussions based on the measurement results

Hotwire turbulence signal

- Sample voltages, v → use calibration fit to find velocity u
- Fluctuating component ~ u-mean(u)
- Compute spectrum of fluctuations
  - E.g.,
    ```
    >> Y = fft(u-mean(u));
    ```
  - Better:
    ```
    >> pwelch(u,[],[],[], Fs);
    >> set(gca, 'Xscale', 'Log');
    ```

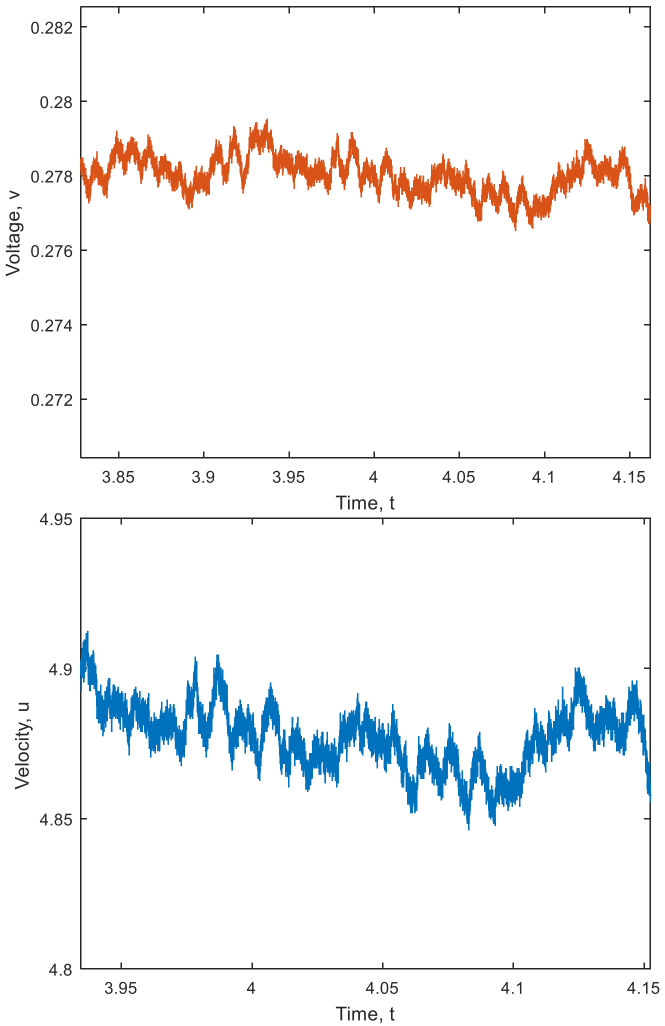


Fig. 1. Time trace of hw signal and velocity

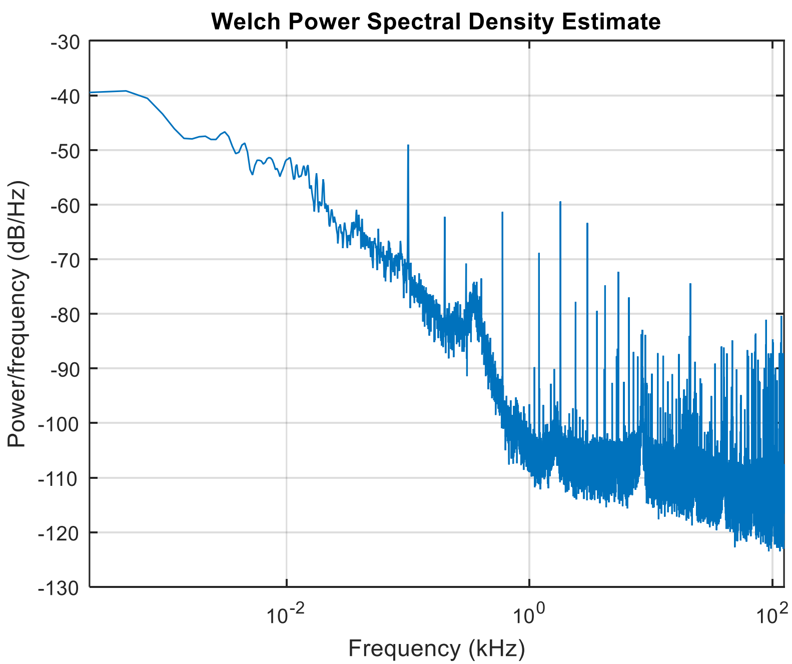


Fig. 2. Spectrum of fluctuations

Summary of the 1st Survey of AerE344 Course

- ***Group size:*** *Most of the students prefer smaller group*
- ***Lecture:*** *Most of students think lectures are helpful*
  - *Sound of the embedded videos is not good…*
  - *Better linkage to the labs*
  - *More "Pre-Lab Videos“ and more on the data analysis*
  - *On what the week's lab is about first, then tie it to the material next.*
- ***Lab:*** *Most of students feel AerE344 labs are helpful for you to better understanding the concepts and principles taught in AerE310 and AerE311.*
- ***TAs:*** *Most of students think the TAs are doing nice jobs.*
  - *Some TAs is restricted from offering as much help as they could, especially when it comes to Matlab.*
- ***Other comments:***
  - *It would be nice to have more guidelines around lab writing and the coding.*
  - *What does the final exam look like*