# 1- Basic Light Interactions & Ray Optics

- Run through the lecture slides AGAIN before you come into lab each week!

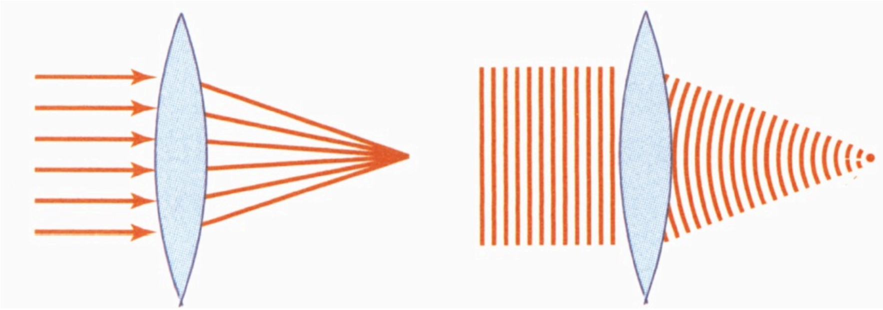
# What is Light?

- Before we can understand any optical system, we need to have a basic understanding of how light interacts with various materials…

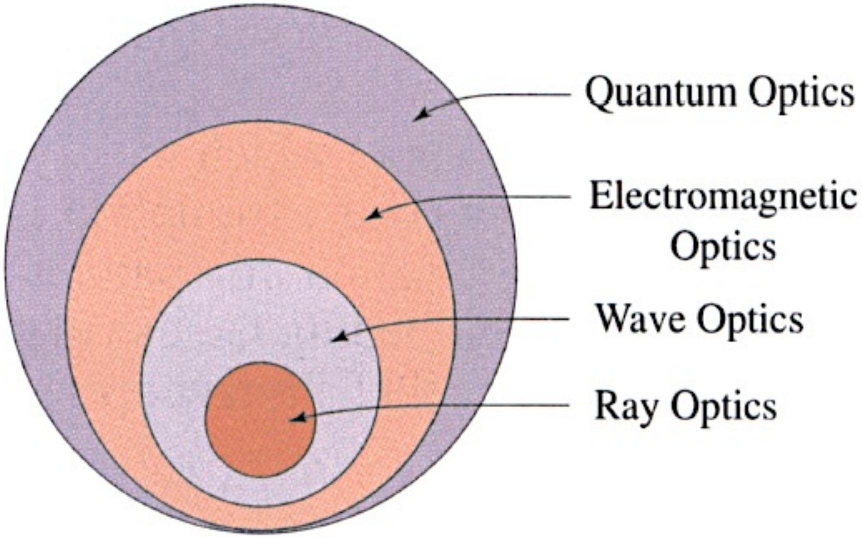
… we could gain an understanding at several levels ranging from a bulk object like a glass prism, down to individual atoms interacting with single photons of light…

… in this course we will limit our understanding to the types of basic interactions (refraction, diffraction, etc..) and basic optical parameters (refractive index, dispersion, etc..) that engineers would utilize in applied optical systems.

- We will spend most of this course on ray and wave optics (shown below).

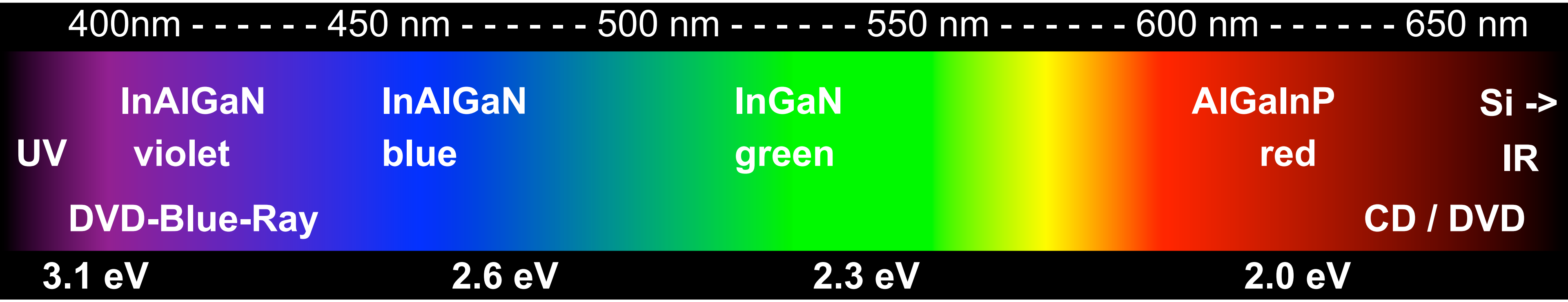


Credit: *Fund. Photonics – Fig. 2.3-1*



Credit: *Fund. Photonics – Fig. 1.0-1*

# What is Light?



400nm - - - - - - 450 nm - - - - - - 500 nm - - - - - - 550 nm - - - - - - 600 nm - - - - - - 650 nm

**UV**

**InAlGaN violet**

**DVD-Blue-Ray**

**InAlGaN blue**

**InGaN green**

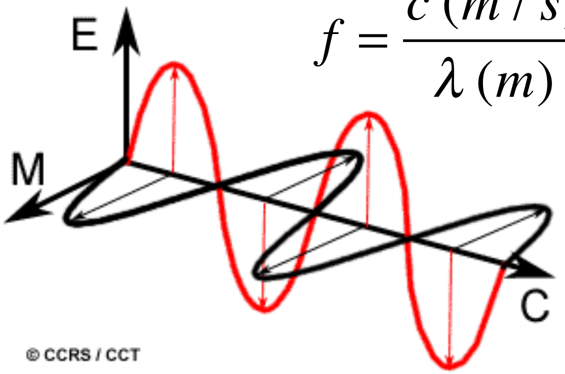
**AlGaInP red**

**CD / DVD**

**Si -> IR**

**3.1 eV** **2.6 eV** **2.3 eV** **2.0 eV**

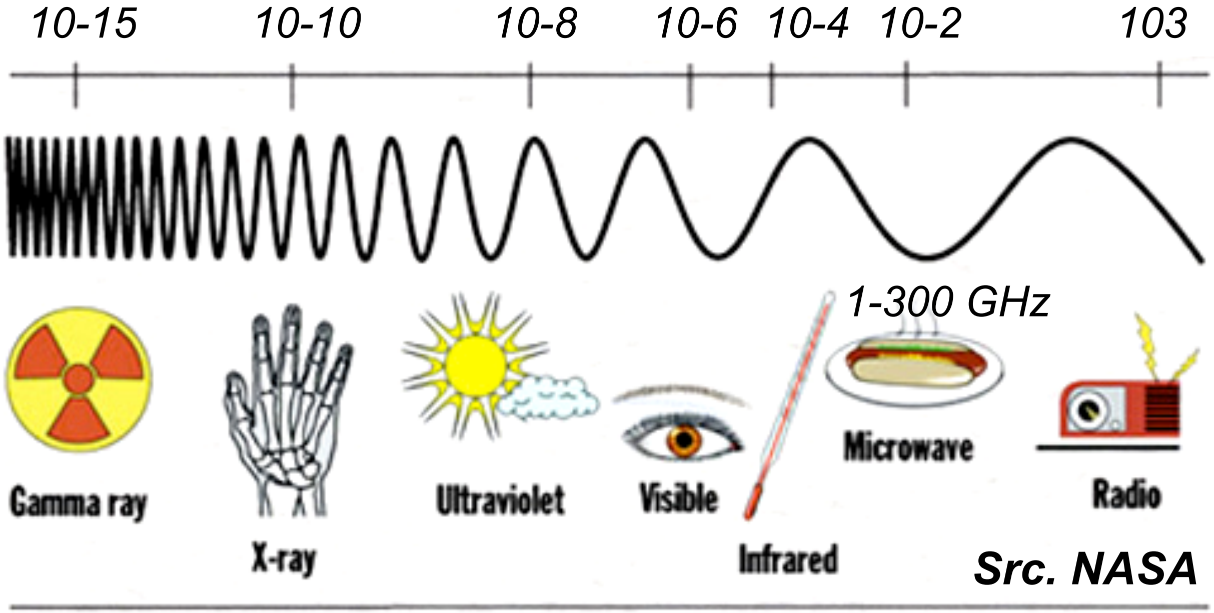
- Light, EM Radiation, Photon, etc…
  - *elementary particle with near zero mass!*



$$f = \frac{c\,(m/s)}{\lambda\,(m)}$$

$$E(eV) = hc/\lambda = hf \quad (also\ h\nu)$$

$$\approx 1240/\lambda(nm)$$

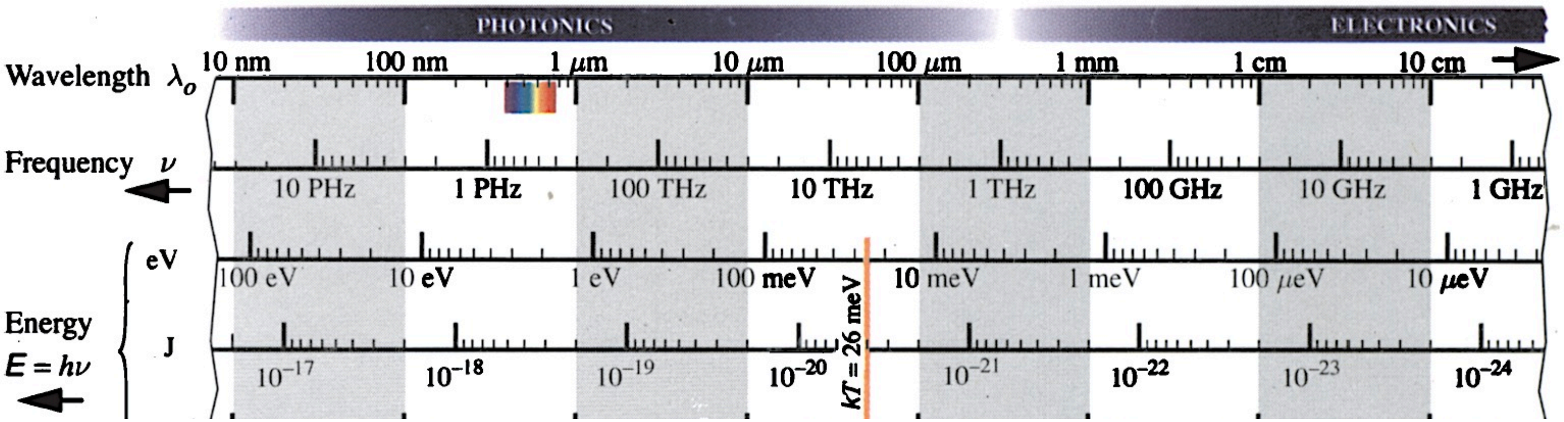


***Src. NASA***

*Why are Gamma, X-ray, and UV harmful? But we are allowed to stick a cell-phone (Microwave) right next to our head?*

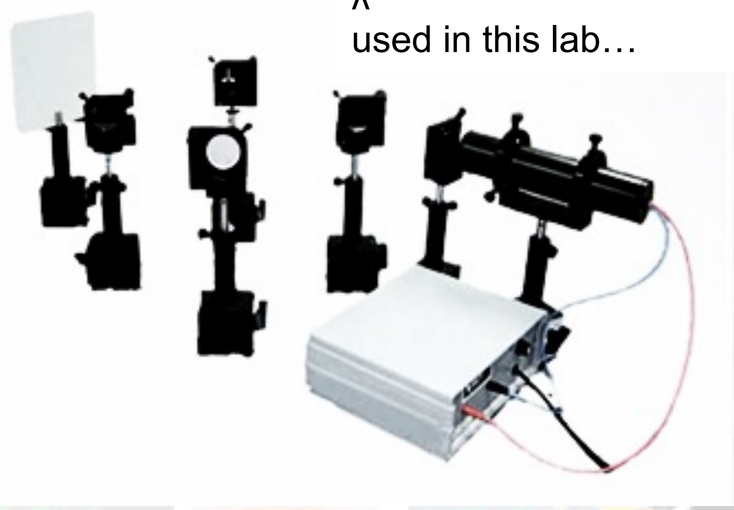
# What is Light?

- This course deals with optics/photonics, not electronics (microwave, millimeter wave, etc..) But radiation is radiation, and the same laws/theories apply to all wavelengths!

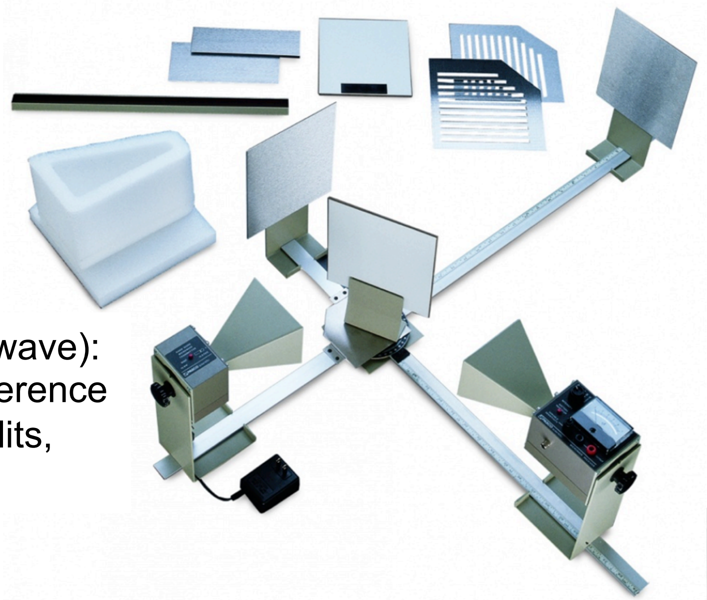


Credit: Fund. Photonics
Back Cover

λ
used in this lab…

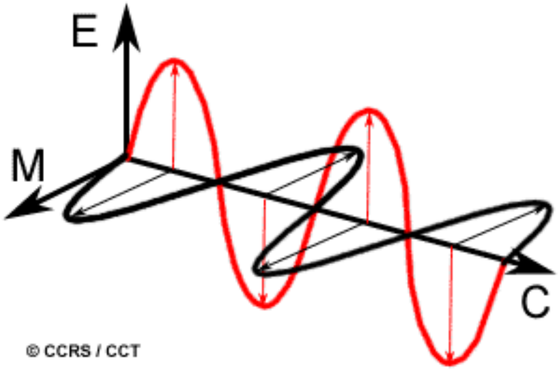


λ ~ 3 cm (microwave):
refraction, interference
and diffraction slits,



# What is Light?

- You could freeze a photon in time (image below) and observe sinusoidal with respect to distance (kx).



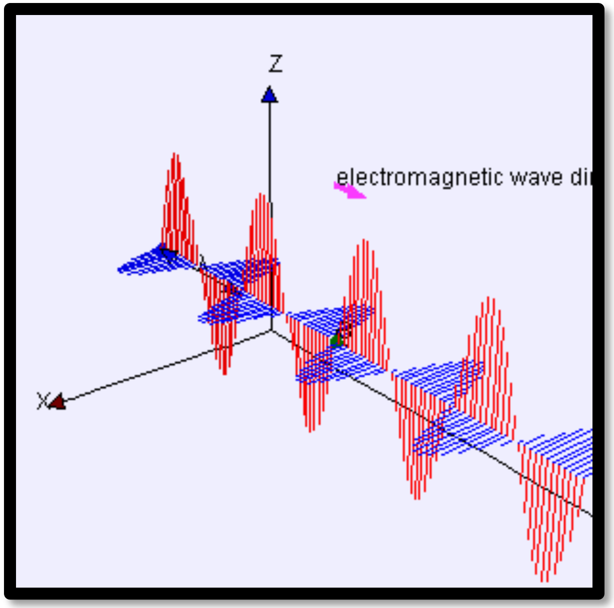
© CCRS / CCT

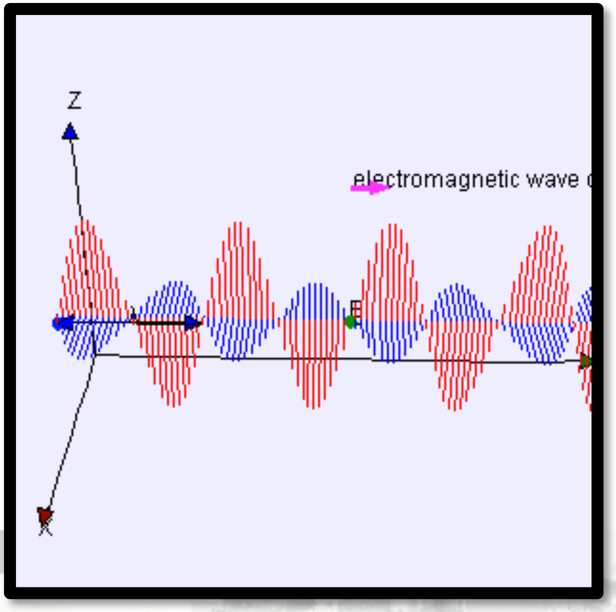
$$E = E_{\max}\sin(wt - kx)$$
$$B = B_{\max}\sin(wt - kx)$$

$$w = angular\ \ freq.\ \ (2\pi f, radians/s)$$
$$k = angular\ wave\ number\ (2\pi/\lambda, radians/m)$$

*For videos google: electromagnetic radiation and pick the wikipedia link.*

- You could also freeze your position and observe sinusoidal with respect to time (wt).
- ***<u>Is just a quantized E&M disturbance! If you remember this, reflection, refraction, etc. make more sense!</u>***

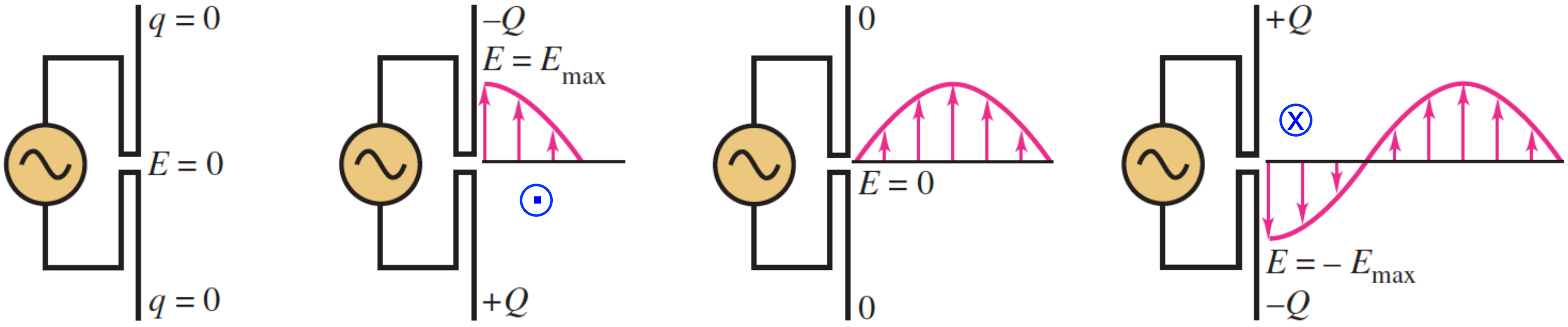




*Animated GIF source: Wiki Commons*

# How A Photon is Created

Credit: Young - Physics



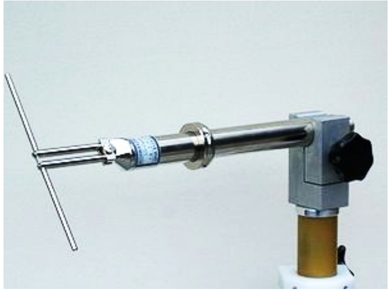
(b) $t = 0$ (c) $t = T/4$ (d) $t = T/2$ (e) $t = 3T/4$

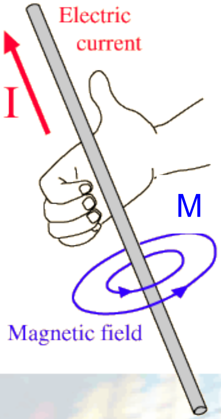
- Consider a simple dipole antenna with two wires each about λ/4 long attached to a 10 GHz sinusoidal voltage(microwave)…

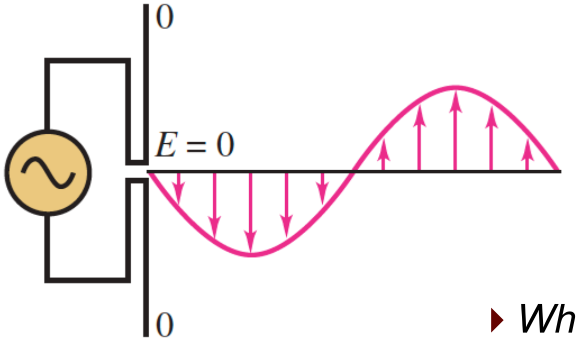
- The voltage hits its 1st positive maximum in ¼ the period, notice the E-field from + to – direction. As current flows 'down' to create the +/-Q, 'M' field is out of the plane.

- In ½ the period V and E = 0 again.

- The voltage hits its first negative max in ¾ the period, E-field from + to – direction. As current flows 'up' to create the +/-Q, 'M' field is into the plane.







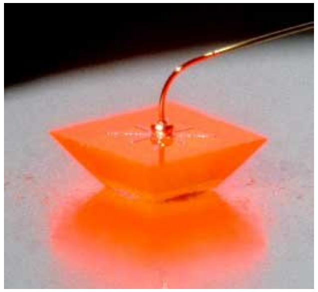
(f) $t = T$

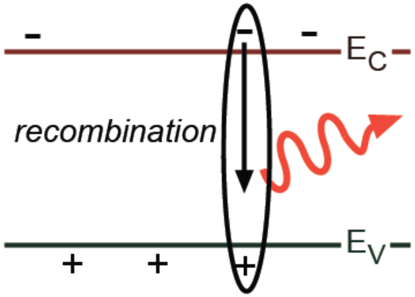
- Cycle complete! These time varying E and M fields sustain each other through freespace!

- *Why were the first mass-broadcasts 'AM radio' @ f~200 kHz?*

# How A Photon is Created

- So how are visible and infra-red photons created? Any guesses? What do we need fundamentally to occur?

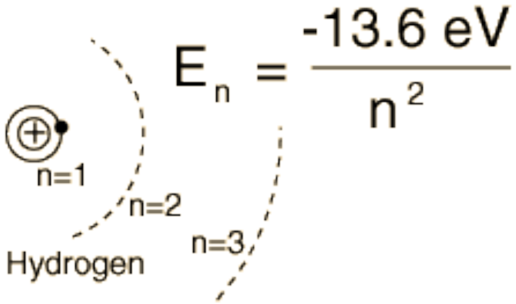




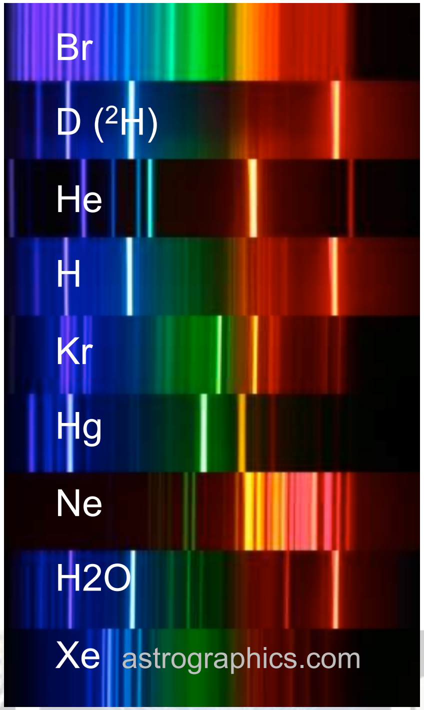
- For semiconductors, also have electric charge that moves and creates E&M fields as it does so!

…but, works only if the bandgap is "direct” (same momentum for electrons and holes). If is indirect, then they have to ‘change direction’ somehow, requiring momentum transfer to the crystal lattice (phonons = vibrations = heat).

- Other common sources are ‘atomic’ transitions…



$$E_n = \frac{-13.6\ \text{eV}}{n^2}$$



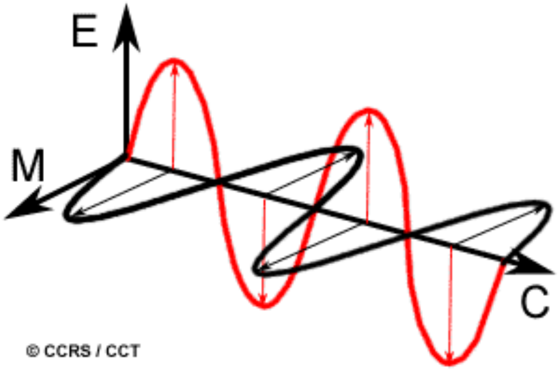
astrographics.com

- Ne is our laser source in the lab!
- How excite the atoms?

# Review! Take a break!

- For the basic principles we are learning in this course, what portions of the electromagnetic spectrum do they apply to?

(a) Visible light.
(b) Visible light and x-rays.
(c) Visible light and microwaves.
(d) Any and all wavelengths.



- What is the most basic thing you need to create a radiator (photon emitter)?

(a) Firewood and a match.
(b) Moving charge creating E&M disturbance.
(c) A metal antenna.
(d) Magic.

- Whew! That's enough. Lets take a break!

Google: 'Charlie Brown Wa Wa Video'

# How A Single Photon Propagates

- In vacuum, light travels at c~3E8 m/s…

- In vacuum, E & M fields only interact with each other…

- In a medium composed of atoms/ molecules, the E & M fields induce a time-varying response in charged particles (e.g. electrons)…

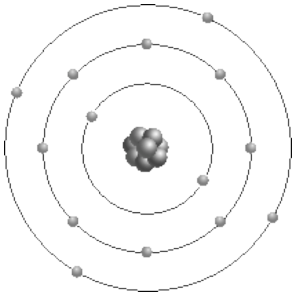
- Most of the ‘motion’ for these charged particles is ‘highly elastic’ and energy temporarily transferred to the particles is returned… <u>but this ‘exchange’ takes time!</u>

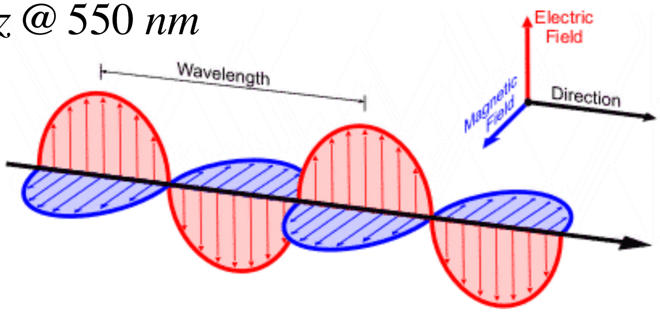
- The more charged particles per unit volume, or the more they can ‘move’ in response to E & M, the slower the light travels in the medium!

- Speed of light in a medium is slowed by the mediums refractive index!

$$v = \frac{c\,(m/s)}{n} \qquad n = \sqrt{\varepsilon_r \mu_r}$$

$$f = \frac{c\,(m/s)}{\lambda\,(m)} = 540\ THz\ @\ 550\ nm$$





# How A Single Photon Propagates

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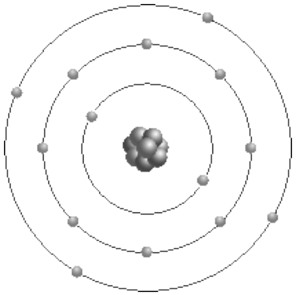
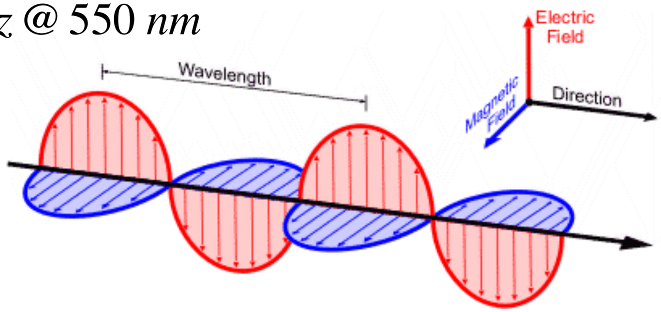




- But wait!!! Water has a dielectric constant of ~80 at 1 kHz! The refractive index is ~1.33 for visible light! This does not compute… why?

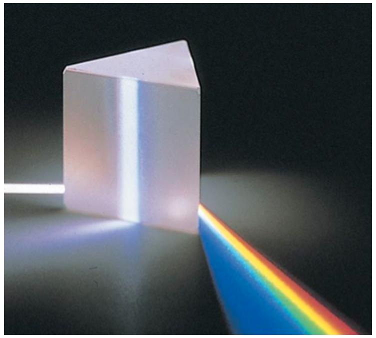
- Most ε's and μ's λ are reported for f~1 kHz (λ=300 km, not relevant to visible light). Generally as you go to 'optical' frequencies like visible, μ goes to 1, and ε decreases because the charged particles can't respond fast enough to the increasingly fast change in E!

| | <u>ε @1 kHz</u> | <u>n @ 500 THz</u> |
|---|---|---|
| Teflon | ε ~2.0 | n~1.3 |
| $SiO_2$ | ε ~4.0 | n~1.5 |
| $TiO_2$ | ε ~80 | n~3.0 |

- But this is not the whole story…

# How A Single Photon Propagates

- Okay, so *ε*, *μ*, and *n* all change with frequency… how might that effect us in visible light applications?



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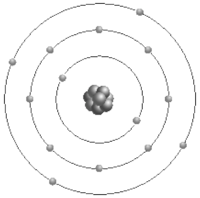
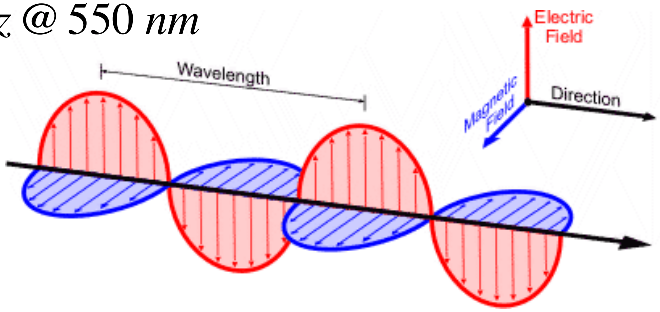
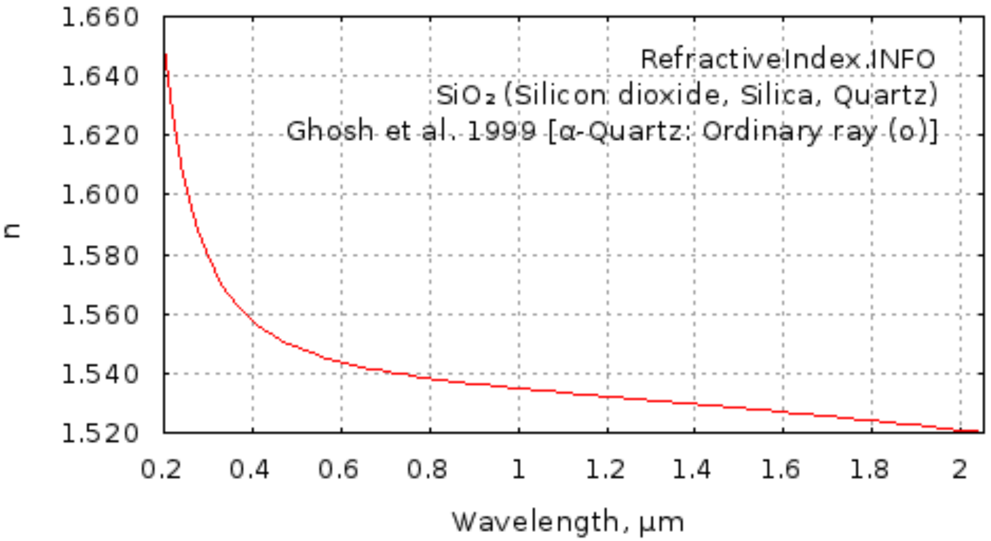




- Refractive index generally goes down with increasing frequency *f* (shorter *λ*), however at some resonant frequencies for a given material it shoots up a bit…

- Change in refractive index with wavelength: Dispersion!



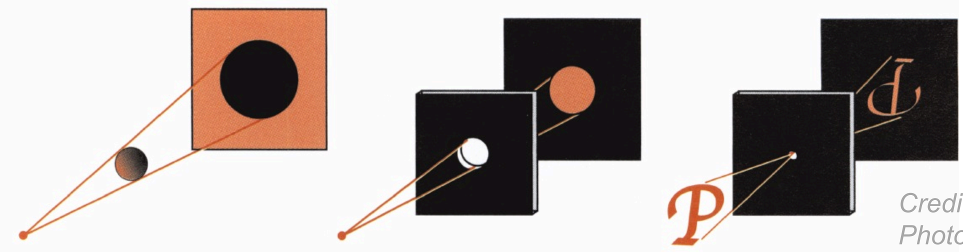
- Top photograph taken with a higher quality lens; bottom is taken with a wide angle lens showing visible chromatic aberration due to dispersion.

wiki/File:Chromatic_aberration_(comparison).jpg

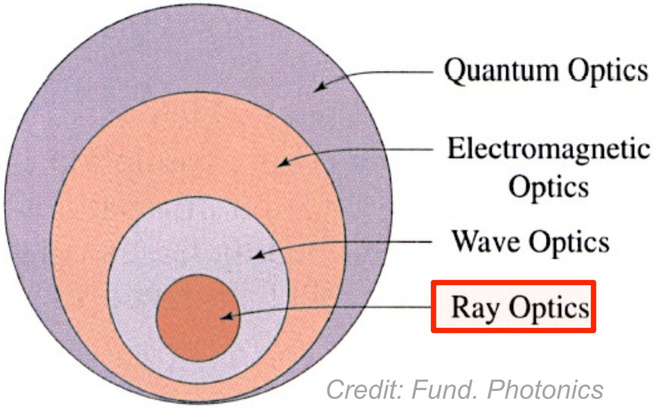
# Postulates of Ray Optics

- There are several basic postulates of Ray Optics:

(1) Light travels in the form of rays…



Credit: Fund. Photonics

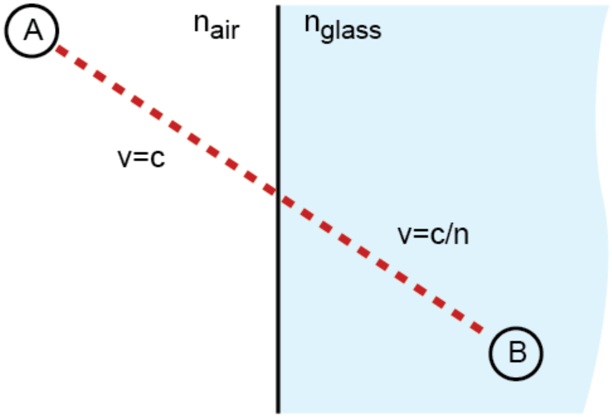


Credit: Fund. Photonics

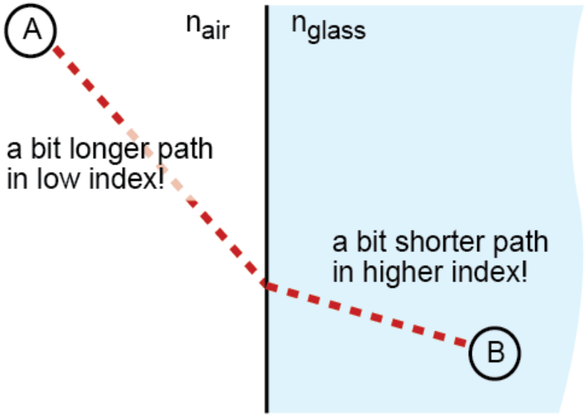
(2) An optical medium slows light by *v=c/n*

(3) The optical path length between any point A and B is *n×d*. Higher index, means longer optical path length (longer time to reach destination).

(4) Light will travel between point A and B <u>taking the path that requires the least time</u> (Fermat's principle)



Question:
← Which →
is faster?



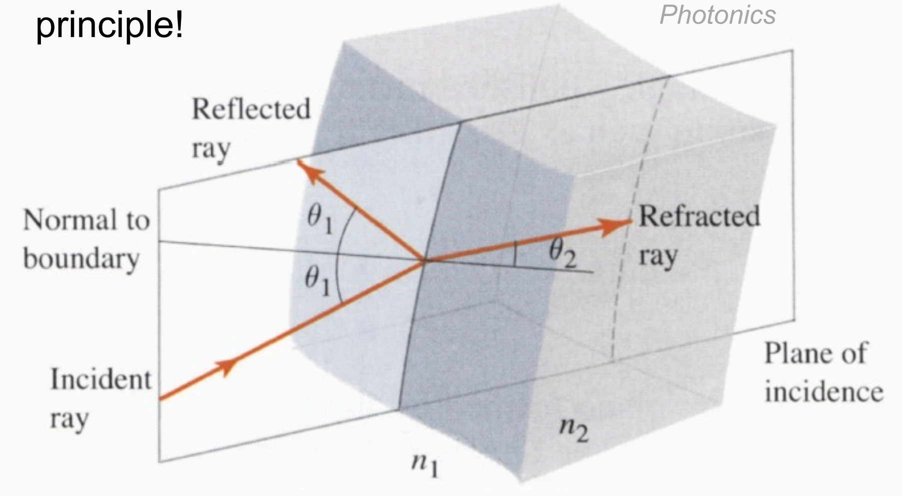
**Pierre de Fermat (1601–1665)** enunciated the principle that light travels along the path of least time.

Credit: Fund. Photonics

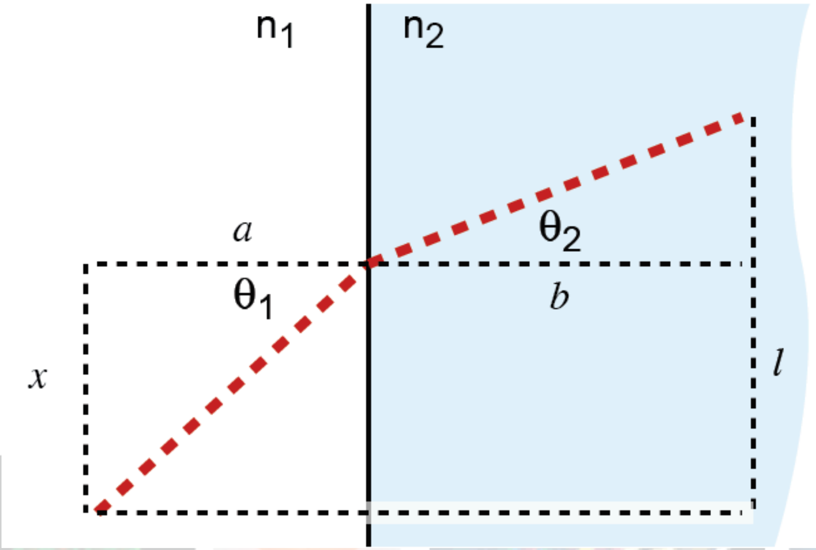
# Ray Optics: Refraction

- Snell's law gives you an equation that predicts angles of refraction according to Fermat's principle!

$$\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$



Credit: Fund. Photonics



- Lets use Fermat's principle and some simple trig to prove this…

(1) the speed of light in each medium is:

$$v_1 = c / n_1 \quad v_2 = c / n_2$$

(2) the total travel time is time=distance/velocity

$$t = \frac{[a^2 + x^2]^{1/2}}{v_1} + \frac{[b^2 + (l - x)^2]^{1/2}}{v_2}$$

(3) there is a minimum travel time, thus altering $x$ from its ideal value will obviously increase this travel time… so we can solve for min time as:

$$\frac{dt}{dx} = 0 = \frac{2x[a^2 + x^2]^{-1/2}}{v_1} - \frac{2(l - x)[b^2 + (l - x)^2]^{-1/2}}{v_2}$$

$$note: \frac{d(l-x)^2}{dx} = \frac{d(l^2 - 2xl + x^2)}{dx} = (2x - 2l) = 2(x - l) = -2(l - x)$$

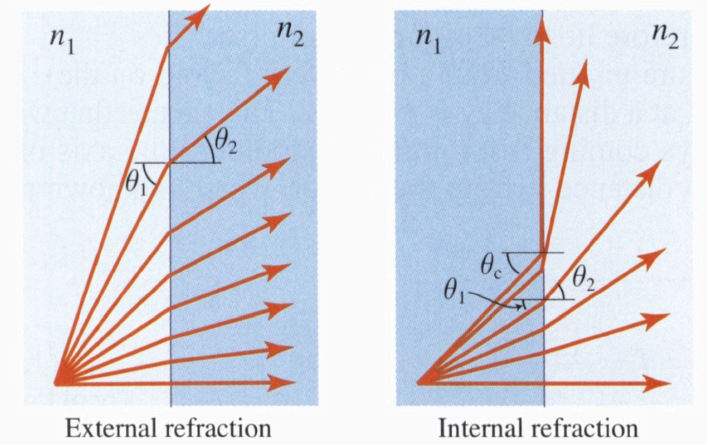
$$\therefore \quad \frac{x}{v_1[a^2 + x^2]^{1/2}} = \frac{(l - x)}{v_2[b^2 + (l - x)^2]^{1/2}}$$

$$\therefore \quad \frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2} \quad \therefore \quad \boxed{\frac{n_1 \sin\theta_1}{c} = \frac{n_2 \sin\theta_2}{c}}$$

# Ray Optics: Refraction

- Look at refraction vs. various incidence angles… Look at the case for internal refraction (high index into low index…), what is this $\theta_C$ thing?

Credit: Fund. Photonics

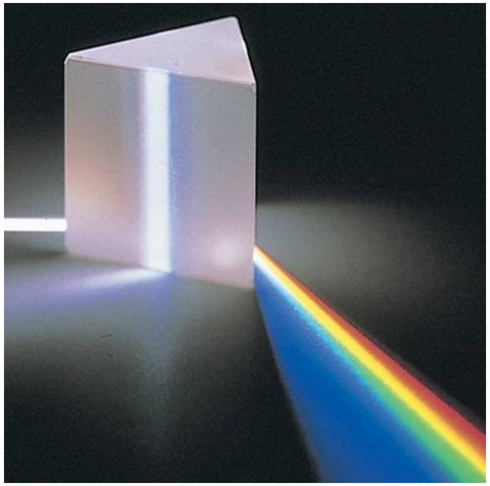


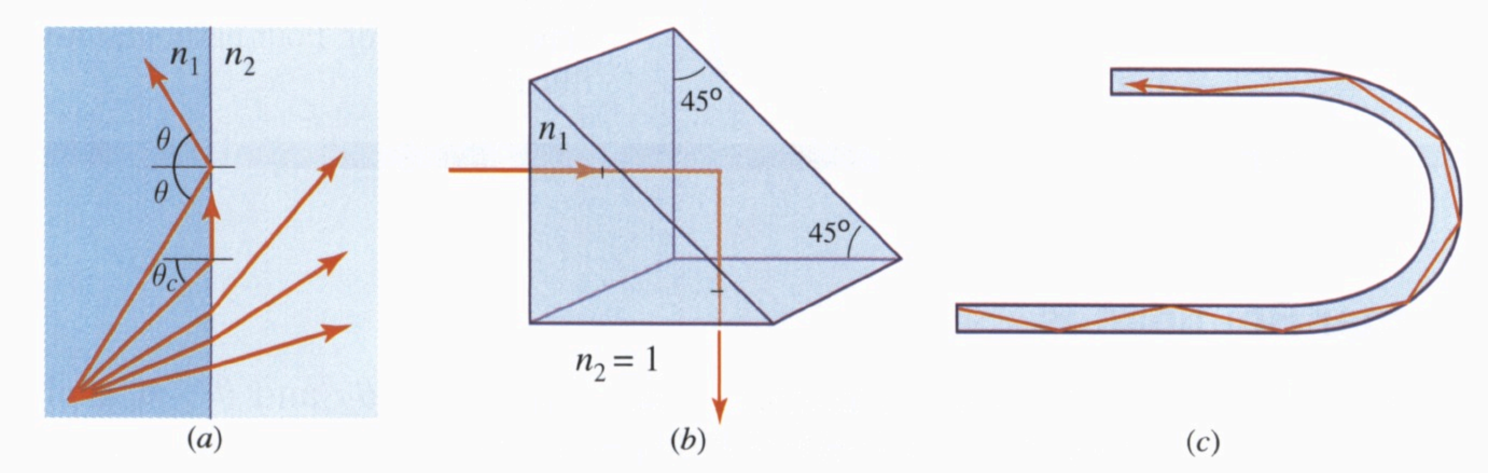
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

- Total internal reflection occurs when you reach the critical angle for the case of $n_1 > n_2$.

$$n_1 \sin\theta_C = n_2 \sin 90$$

$$\boxed{\theta_C = \sin^{-1}(n_2 / n_1)}$$





# Review! Take a break!

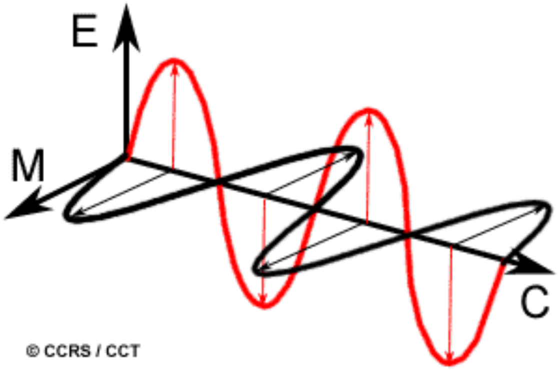
- How do you calculate refractive index, and why? What do you need to be careful of?

(a) Based on permittivity ε.
(b) Based on permeability μ.
(c) Corrected ε and μ for frequency (they change with frequency).
(d) All the above.

- A prism, or a 'cheapy' lens splits white light into colors, why?

(a) The surface of the prism is rough.
(b) Refraction changes with wavelength (colors).
(c) The magnetic field is slowed down.
(d) Magic.

- What does Fermat's principle say basically, for any type of optical element or system?



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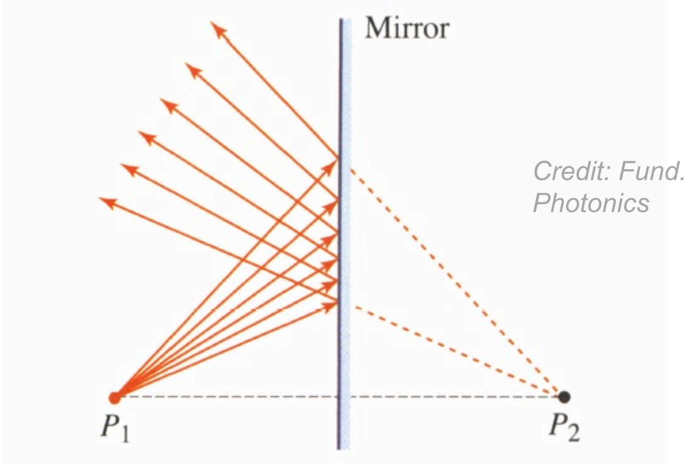
- Whew! That's enough. Lets take a break!

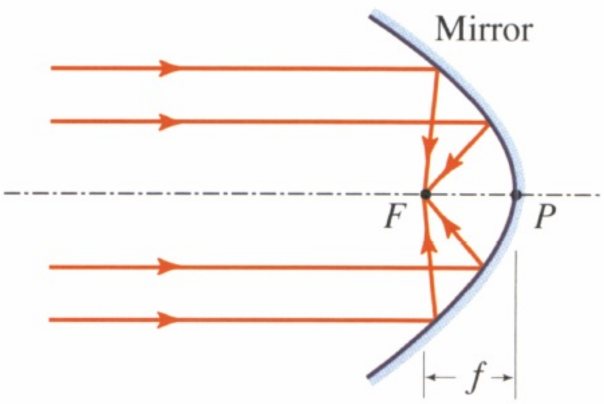
# Ray Optics: Reflectors

- Mirror reflector (is specular, and planar)



*Credit: Fund. Photonics*

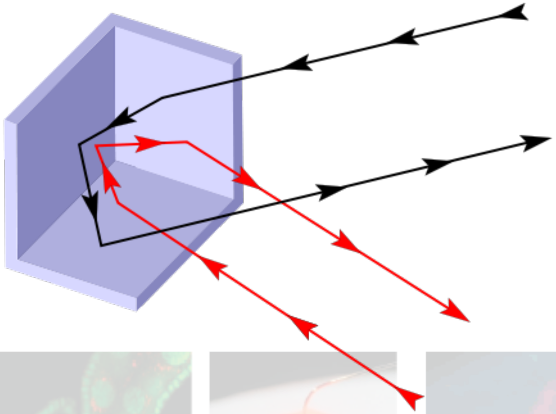
- Parabolic reflector ($x^2$)



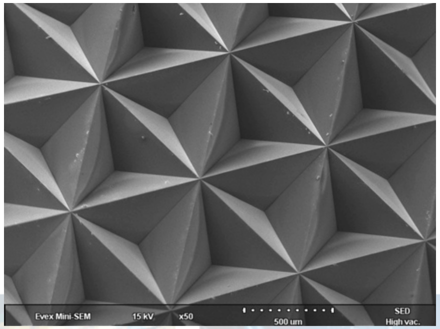
Question, how is a parabolic reflector useful? Think of two applications, think of light emission or light absorption.

- Retroreflector (corner cube)

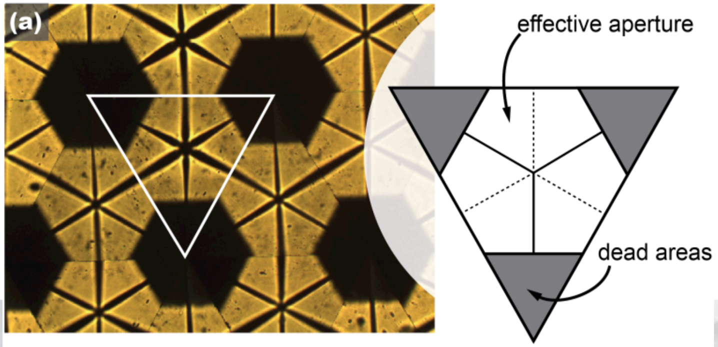
Three normal vectors of the corner's sides form a basis (x, y, z). When an incoming ray, [a, b, c] reflects from the first side, say x, the ray's x component, a, is reversed to -a. Reflection from sides y and z [-a,-b,-c] reverses the other components. Need 3 reflections!



SEM photo.



Optical photo of retroreflection, why dead area?

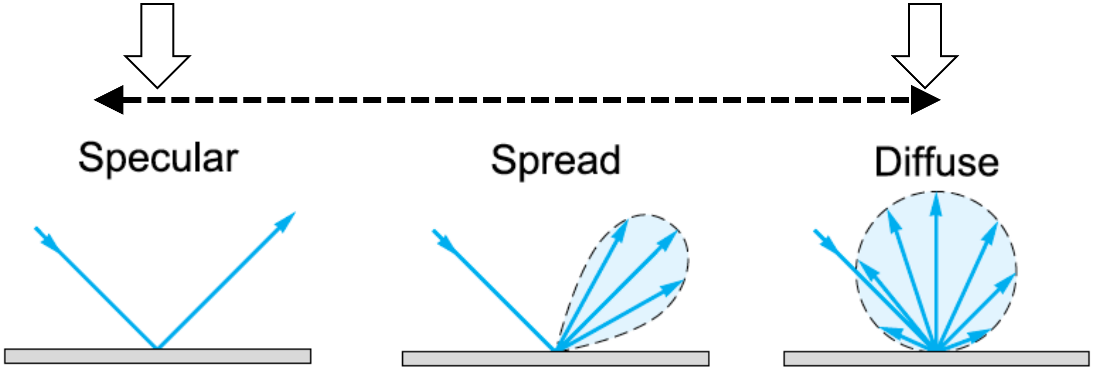


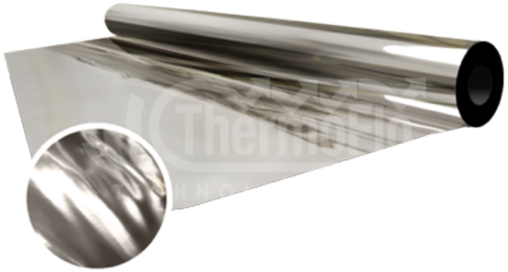
# Ray Optics: Specular vs. Diffuse

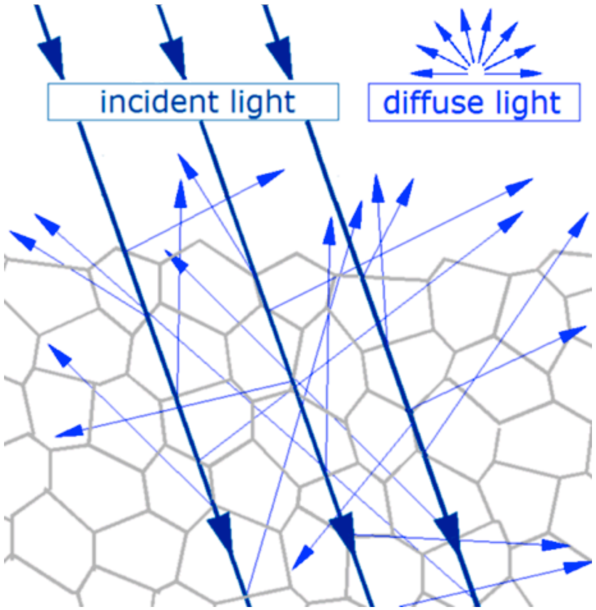
- Not all reflection is mirror like (specular)… some reflections are diffuse (Lambertian).

*Appears
silver and
lots of glare.*

*Appears
white from
all angles.*







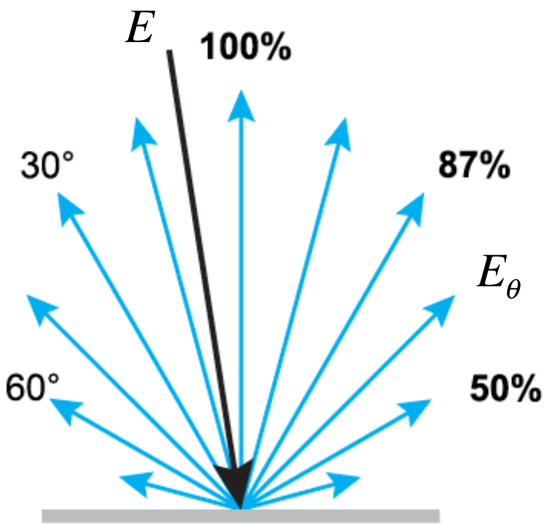
*Diagrams from Alex Ryer, International Light, "Light Measurement Handbook" – strongly recommended!*

# Ray Optics: Specular vs. Diffuse

- Diffuse (Lambertian) reflection is mathematically sophisticated and unique…

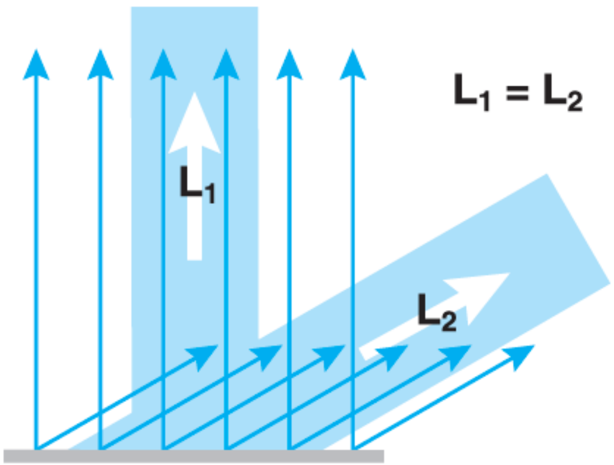
(1) Lambert's cosine law: the intensity reflected is decreased as cos(θ) from the surface normal.

$$E_\theta = E \times \cos(\theta)$$



(2) However! The luminance (observed brightness) stays constant with θ because the surface area observed increases with θ!

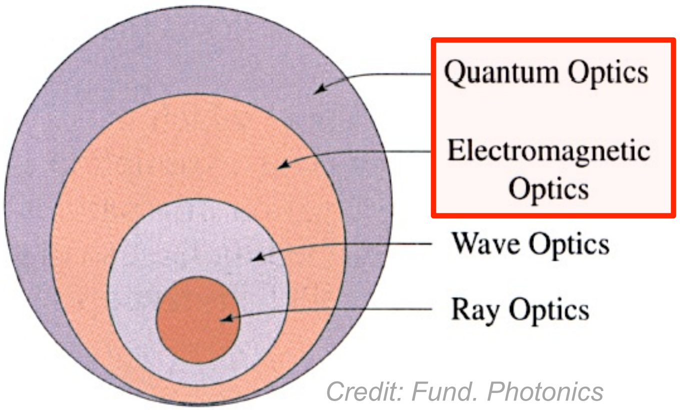
$$L_1 = L_2$$



*Diagrams from Alex Ryer, International Light, "Light Measurement Handbook" – strongly recommended!*

# Fresnel Reflection

- Next topic requires quantum/electromagetic understanding beyond the focus of this course. In 1678, Huygens proposed that every point to which a luminous disturbance reaches becomes a source of a spherical wave. You can solve all optics this way!



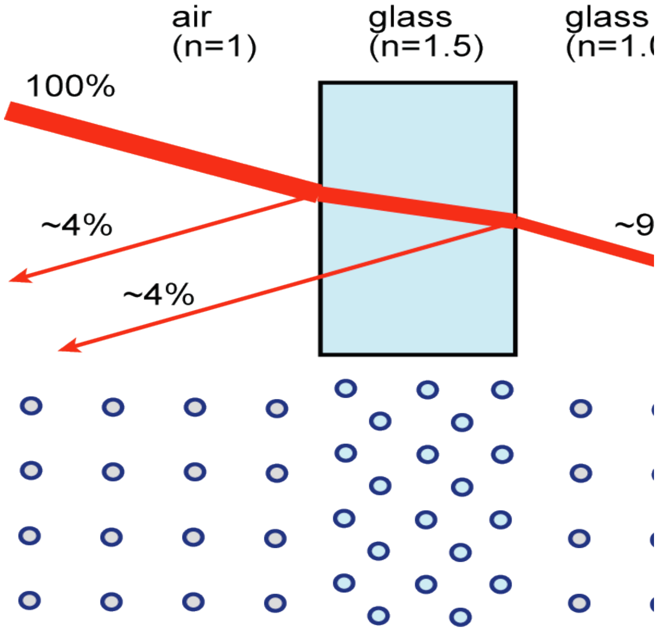
*Credit: Fund. Photonics*

- Now, it turns out that interference only allows forward propagation through a homogeneous medium (air, glass), more on this in week 4… But what if inhomogeneous?

- As light enters glass the electric field oscillates valence electrons (orbits), these oscillations act as a new dipole radiator which emits light as a weak <u>Fresnel reflection</u> (5-10%, comes from in the glass, but seen as surface effect).

- In metals, tons of electrons that move freely in the electric field. Effect is stronger (reflect to 95%), but moving electrons cause ohmic loss (imperfect reflection).

- For incident angles close to zero, the Fresnel Reflection is:



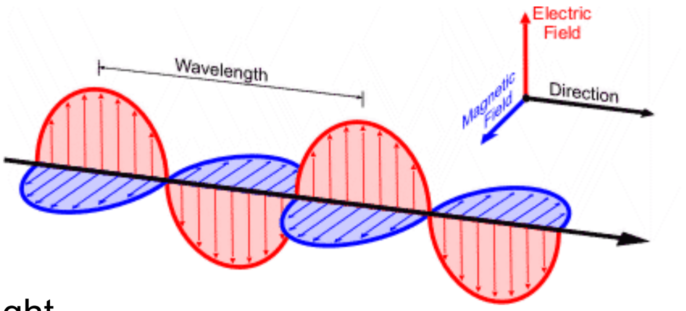
$$\%R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

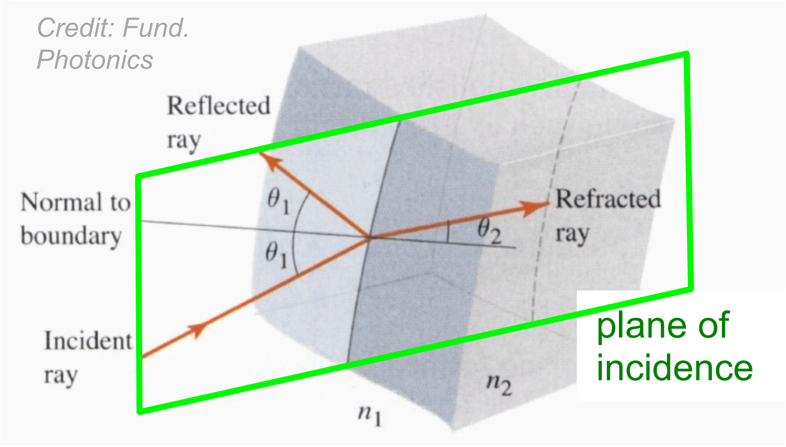
$$\%R = \left(\frac{1.0 - 1.5}{1.0 + 1.5}\right)^2 \approx 0.04$$

For other angles, see next slide…

# Fresnel Reflection

- For non-zero incidence angles…



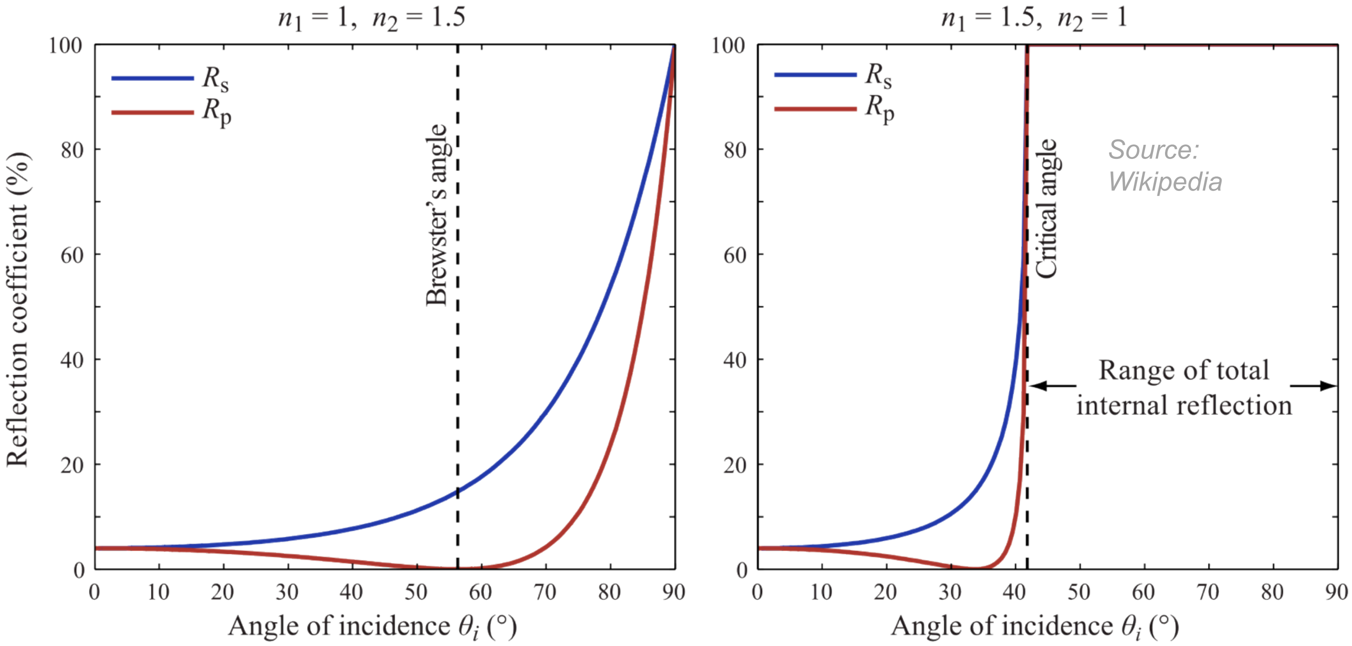

Credit: Fund. Photonics

(1) For s-polarized light magnetic field is parallel to the plane of incidence

$$\%R_S = \left( \frac{n_1 \cos\theta_1 - n_2 \cos\theta_2}{n_1 \cos\theta_1 + n_2 \cos\theta_2} \right)^2$$

(2) For p-polarized light electric field is parallel to the plane of incidence

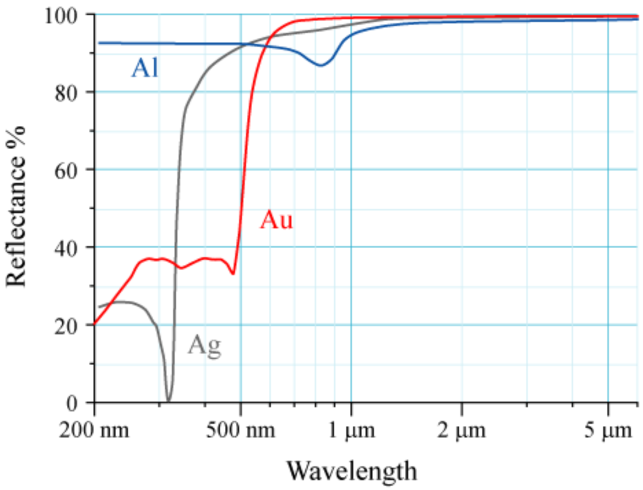
$$\%R_P = \left( \frac{n_1 \cos\theta_2 - n_2 \cos\theta_1}{n_1 \cos\theta_2 + n_2 \cos\theta_1} \right)^2$$


Source: Wikipedia

Note, the s and p convention varies and so do alternate names such at TE and TM. Be careful!

# Mirror Quality Varies

- There are conventional mirrors

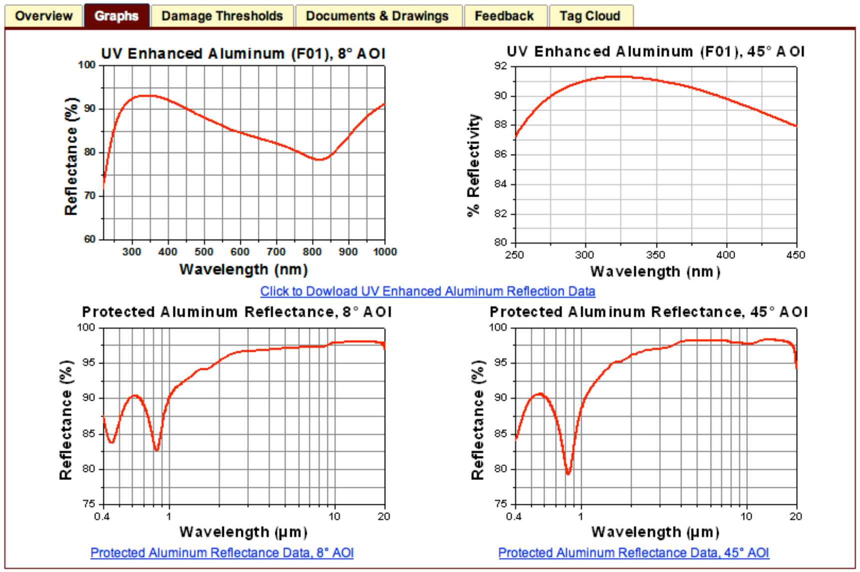


- There are combinations of both called 'enhanced mirrors'

THORLABS


**UV Enhanced and Protected Aluminum Mirrors**

- Enhanced $R_{avg}$ > 90% from 250 – 450 nm
- Protected Aluminum $R_{avg}$ >90% from 450 nm to 2 µm, $R_{avg}$ >95% from 2 – 20 µm
- Engraved with Item # on Back

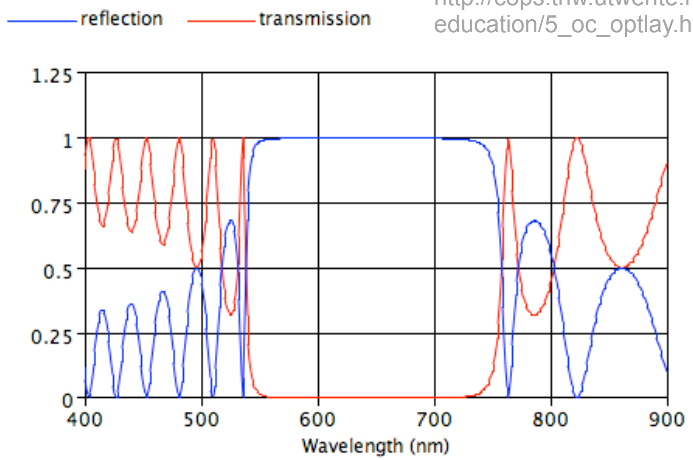


Click to Dowload UV Enhanced Aluminum Reflection Data

Protected Aluminum Reflectance Data, 8° AOI

Protected Aluminum Reflectance Data, 45° AOI

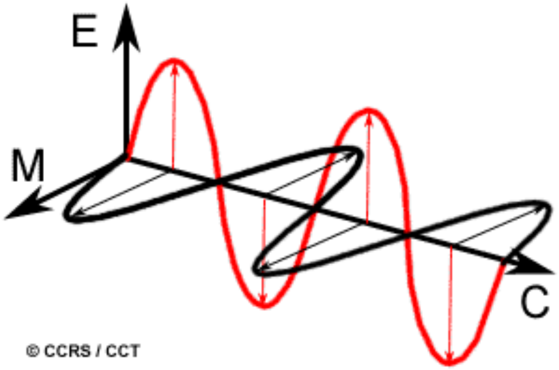
- There are dielectric mirrors (will explain how they work in lecture 3)



http://cops.tnw.utwente.nl/education/5_oc_optlay.html

- A diffuse (Lambertian) reflector looks just as bright even when you view it at wide angles, why?

(a) The amount of reflected intensity is the same.
(b) The amount of reflected intensity decreases.
(c) The amount of area your eye captures increases.
(d) Both answers (b) and (c).



© CCRS / CCT

- In which case will glass reflect light strongly due to Fresnel reflection:

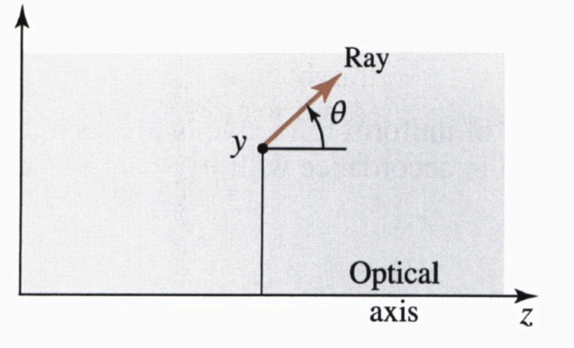
(a) When placed in air or vacuum.
(b) When placed in an oil with the same refractive index as the glass.
(c) Neither (a) or (b).
(d) Both (a) and (b).

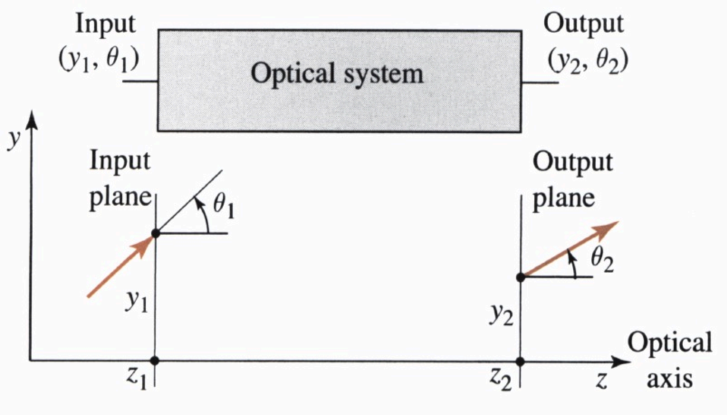
- Whew! That's enough. Lets take a break!

# Ray Transfer Matrices

- Ray transfer matrices simplify calculations, especially with numerous optical elements in series. We will not do these in this lab, you might consider doing some of this as a final project with MATLAB!

Credit: Fund. Photonics





(1) All reflections can be determined by based on $\theta_1$, and all refractions determined based on sin $\theta_1$

(2) For small incident angles (typical case with most optics) the relation between $y_1,\theta_1$ and $y_2,\theta_2$ is approx. linear. (A,B,C,D, are real numbers). Remember, this approx. requires units radians, not degrees!

$$1\,rad = 180° / \pi \approx 57.3°$$

$$\sin\theta_{rad} \approx \theta_{rad} \quad for\ small\ \theta_{rad}$$

$$5.7° \Rightarrow \sin 0.1 \approx 0.0998\,(0.17\%\ error)$$

$$11.5° \Rightarrow \sin 0.2 \approx 0.1987\,(0.65\%\ error)$$

$$17.2° \Rightarrow \sin 0.3 \approx 0.2955\,(1.5\%\ error)$$

$$22.9° \Rightarrow \sin 0.4 \approx 0.3894\,(2.6\%\ error)$$

$$\therefore y_2 = Ay_1 + B\theta_1$$

$$\therefore \theta_2 = Cy_1 + D\theta_1$$

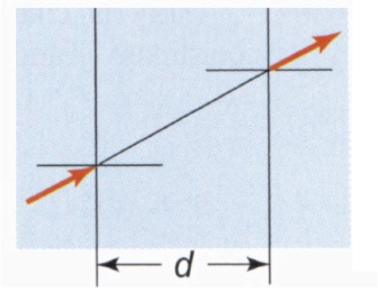
- You can then represent optical systems or components as row by column ABCD 2x2*2x1=2x1 matrices!

$$\begin{bmatrix} y_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix} \Rightarrow \begin{aligned} y_2 &= Ay_1 + B\theta_1 \\ \theta_2 &= Cy_1 + D\theta_1 \end{aligned}$$

# Ray Transfer Matrices

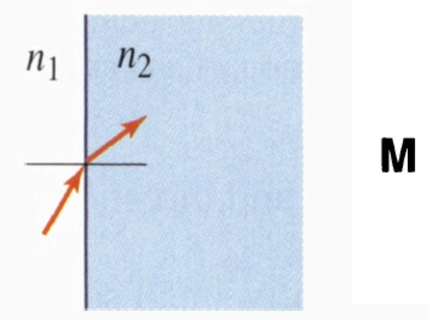
$$\begin{bmatrix} y_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix}$$

- Propagation over distance *d*



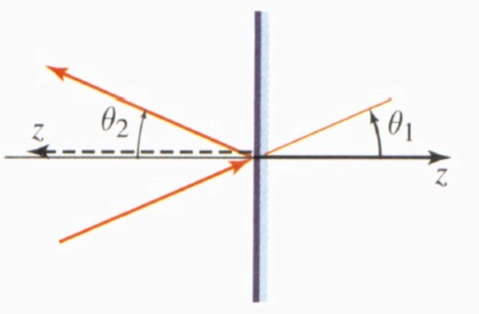
$$\mathbf{M} = \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix}$$

- Refraction



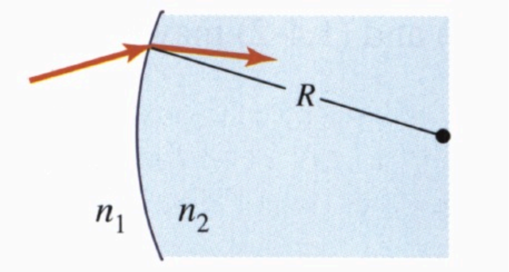
$$\mathbf{M} = \begin{bmatrix} 1 & 0 \\ 0 & \frac{n_1}{n_2} \end{bmatrix}$$

- Reflection (Identity matrix)



$$\mathbf{M} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

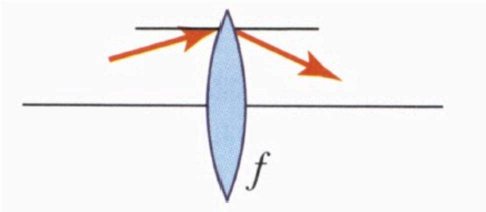
- Refraction at spherical surface



Convex: $R > 0$; concave: $R < 0$

$$\mathbf{M} = \begin{bmatrix} 1 & 0 \\ -\frac{(n_2 - n_1)}{n_2 R} & \frac{n_1}{n_2} \end{bmatrix}$$

- Lens (will cover next lecture…)

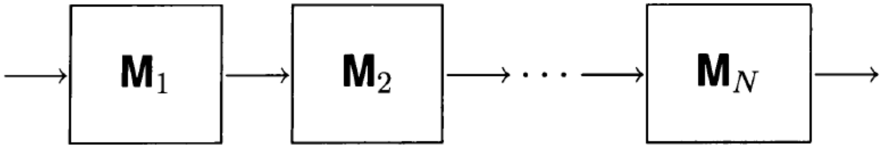


Convex: $f > 0$; concave: $f < 0$

$$\mathbf{M} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix}$$

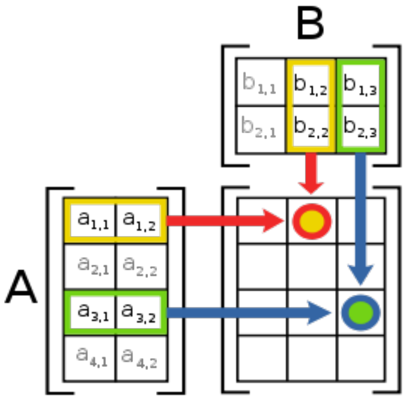
# Ray Transfer Matrices

- Multiple optical elements? Just multiply the respective matrix representations for each optical element!

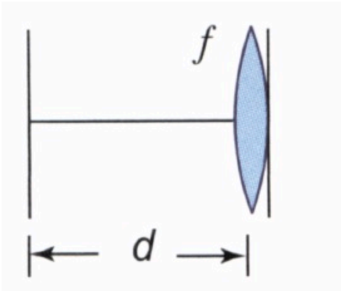


*note the order…

$$\mathbf{M} = \mathbf{M}_N \cdots \mathbf{M}_2\mathbf{M}_1$$



- How about a lens of focal length *f* at a distance *d?*

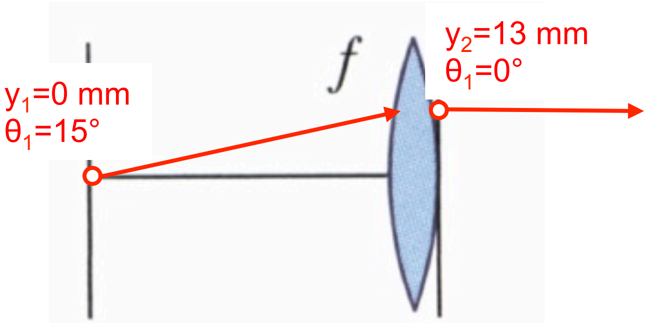


$$\begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix} \times \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1+0 & d+0 \\ -1/f+0 & -d/f+1 \end{bmatrix} = \begin{bmatrix} 1 & d \\ 0-1/f & 1-d/f \end{bmatrix}$$

- What is $y_2$,$\theta_2$ if d= 50 mm, f= 50 mm, $y_1$=0 and $\theta_1$=15° (0.26 rad)? *(starting at focal point, so we know $\theta_2$ should be zero, more on that next lecture…).*

$$\begin{bmatrix} y_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} 1 & d \\ 0-1/f & 1-d/f \end{bmatrix} \times \begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix} = \begin{bmatrix} y_1 + d\theta_1 \\ -y_1/f + \theta_1 - d\theta_1/f \end{bmatrix}$$

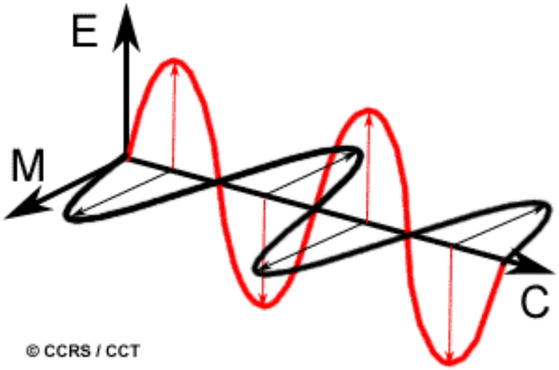
$$= \begin{bmatrix} 0 + 50\times 0.26 \\ 0 + 0.26 - 50\times 0.26_1/50 \end{bmatrix} = \begin{bmatrix} 13\,mm \\ 0\,rad \end{bmatrix}$$



# Review! Take a break!

- Why bother with Ray Transfer Matrices?

(a) They save you time.
(b) They give you a more accurate result.
(c) Neither (a) or (b).
(d) Both (a) and (b).

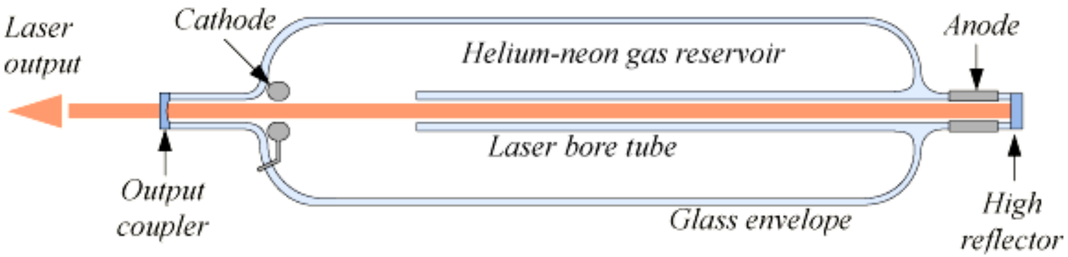


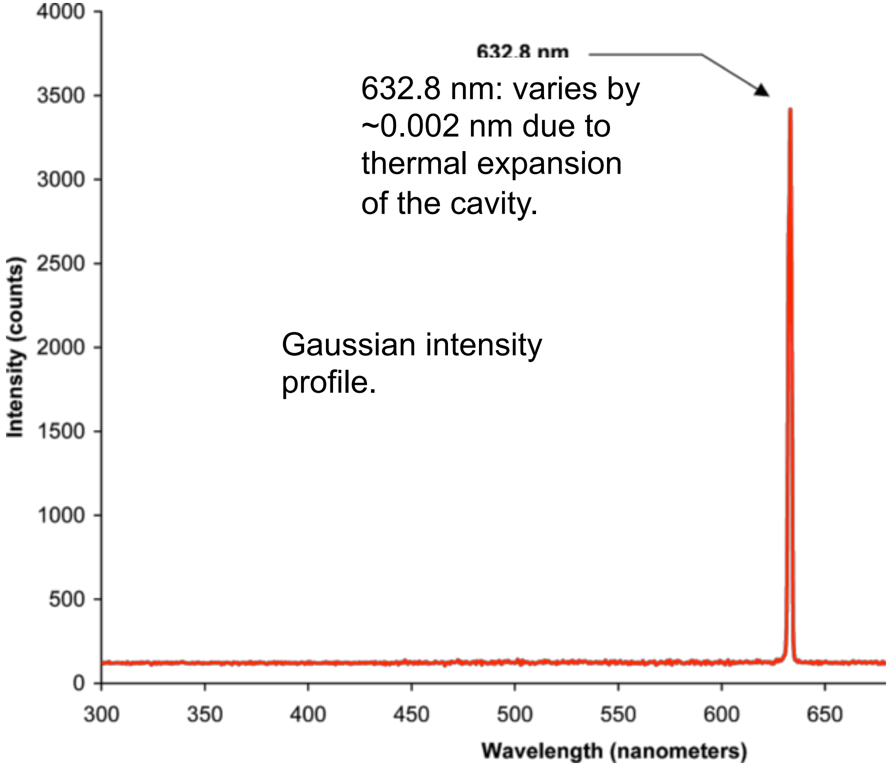
- Whew! That's enough. Lets take a break!

# About The Laser

- **L**ight **A**mplification via **S**timulated **E**mission and **R**esonance

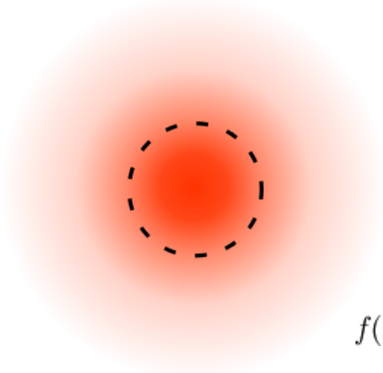
- Operates via ~1000 VAC, plenty of eV!, careful of shock!



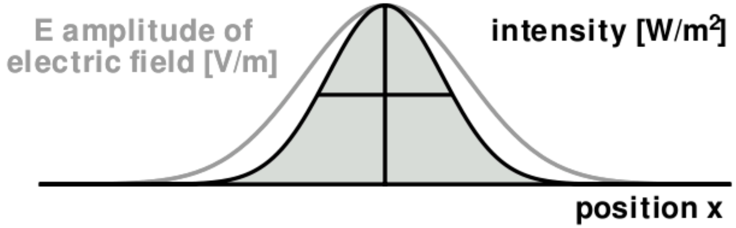


632.8 nm: varies by ~0.002 nm due to thermal expansion of the cavity.

Gaussian intensity profile.



$$f(x) = ae^{-\frac{(x-b)^2}{2c^2}}$$



# About The Detector

- There is the Si PIN photodiode

- converts photons to electrical current
- has ~1 $cm^2$ active area
- mounts easily on a post
- damaged if >1 $W/cm^2$ … Laser is only ~1 mW, should we worry?

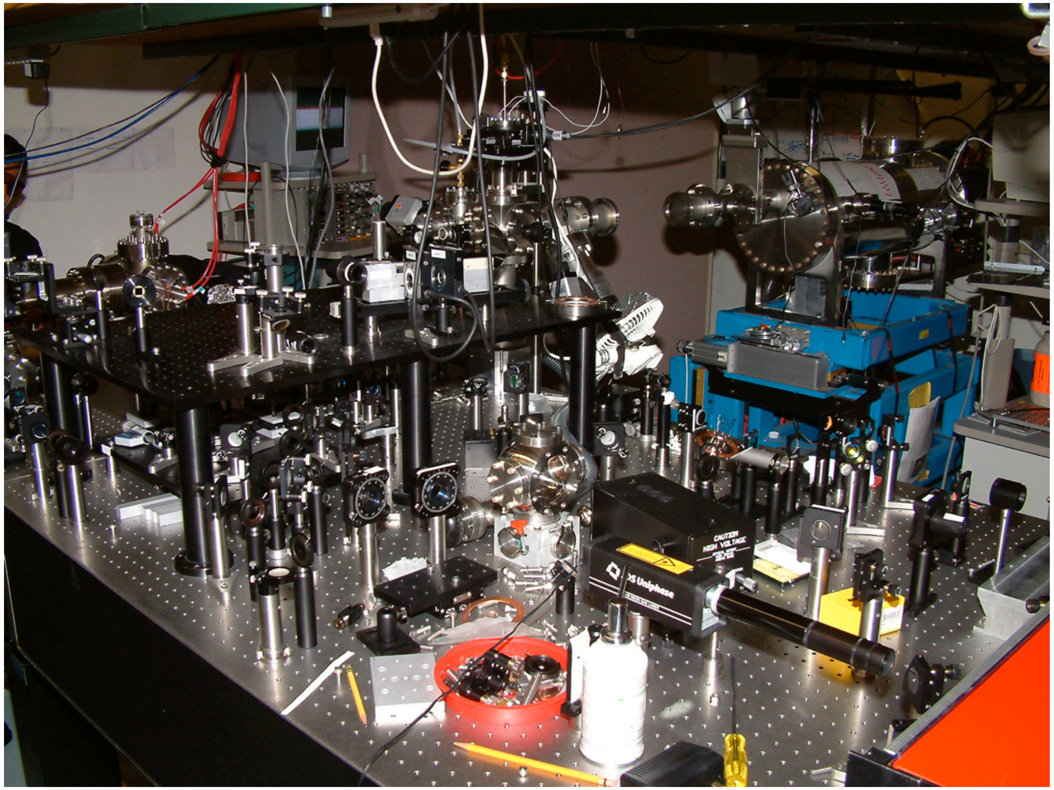
- There is the attenuator (100X)

- protect photodiode from damage if needed…
- prevent detector saturation (bright light)

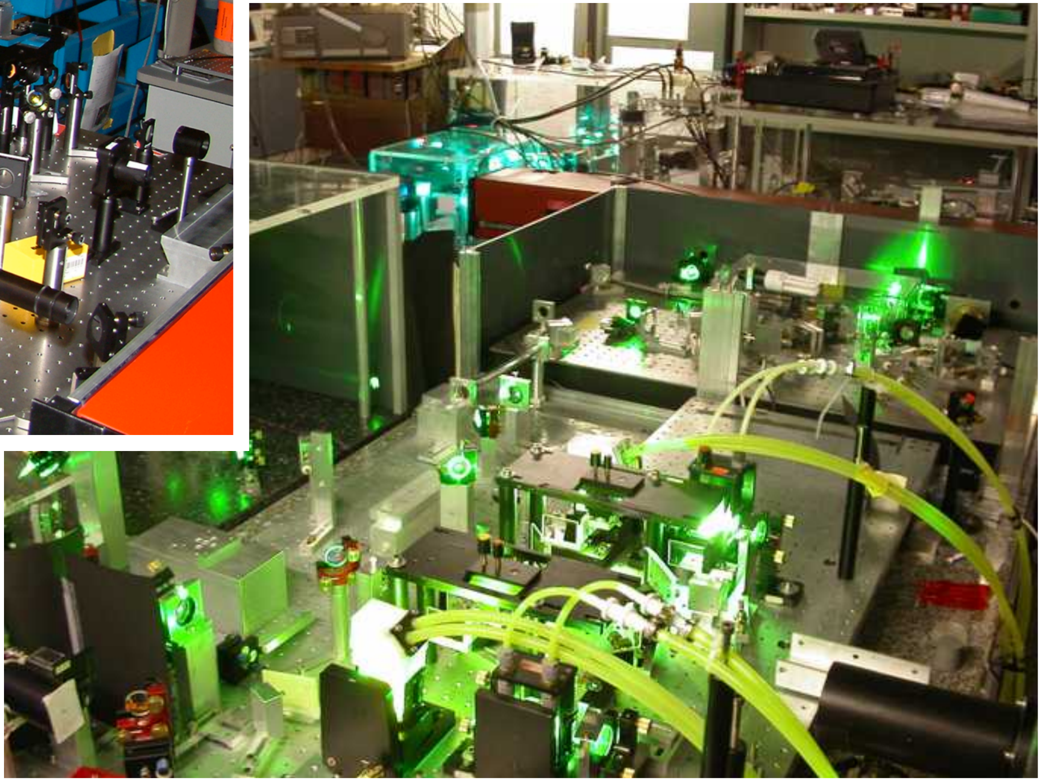
- There is the power meter (provides power to the detector and converts current from the detector to optical power

- for some there is a wavelength setting plus a few other features (see manual)

# About Alignment



- The Laser should never go above table level, out a door or window, and if you need to bring your head down to the level of the laser then just turn it off to be safe!



- Add a part, then with a mirror reverse it back to the laser, then add a part, then reverse it again… etc…

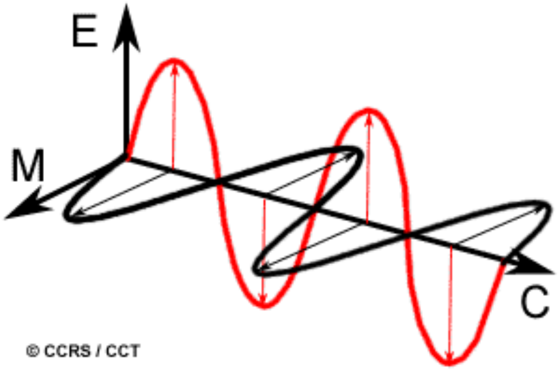
- A white card with a hole on it in front of the laser helps…

- If you disconnect the laser cord and stick the cord on your skin or tongue will you be glad or very very sorry?

- Why should you always keep your laser below eye level in the lab? Is it more dangerous in a dark or a light room?

- What is the best way to assemble an optical system?

(a) Add all the parts at once.
(b) Add them one by one, reversing the laser light as you go to make sure they are aligned.
(c) Either (a) or (b).
(d) Neither (a) nor (b).



- Whew! Were done with Lecture 1!