Chapter 1
Basic Properties of Light

Light is described using 3 pictures - seemingly contradictory!

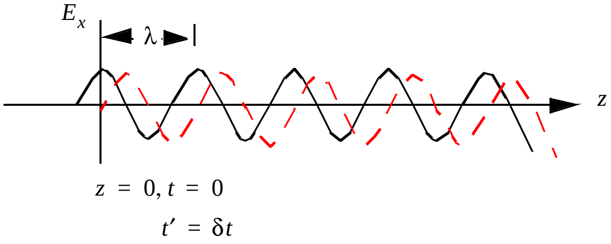
Waves - Rays - Photons

Waves

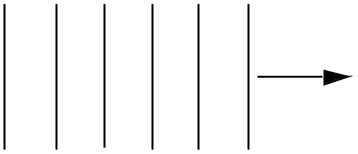
[Reading Assignment: Hecht, Chapter 2 (most of this should be review), 3.2, 3.3, 3.4.4, 3.5, 3.6]

A propagating "disturbance" in *electric* and *magnetic* field (simultaneously!)

Example: $$\boxed{\vec{E} = E\hat{x}\cos\left(\frac{2\pi}{\lambda}z - 2\pi f t\right)}$$



- At a fixed point in space, the electric field oscillates in time. At a fixed point in time, we see a wave train frozen.
- This is called a plane-wave because the field is constant everywhere in the x-y plane at a given z. Another way to draw this is



"wave-fronts" surface of constant "phase" or "phase-fronts"

- The wavefront advances by a distance λ, in a time $1/f$. So the velocity is $\text{v} = \text{distance/time} = \lambda f$. One of the many remarkable properties of light is it's universal, constant speed:

$$\boxed{c = 2.997 \times 10^8 \text{ m/sec}} \qquad \boxed{c = \lambda f} \text{ in vacuum}$$

- The physics of electromagnetic (EM) wave propagation is valid for arbitrary λ, f. On Earth, we can generate, manipulate and/or detect EM waves with wavelength from ~100 km all the way down to $\sim 10^{-6} A°$. Usually we describe light by wavelength rather then frequency, except in the microwave and radio regions.

- The electromagnetic spectrum encompasses the complete range of frequency/wavelength. Different regions have different names. Radio, microwave, infrared, visible, ultraviolet, x-ray, γ-ray.

Index of Refraction

- When light travels in materials, the speed is modified:

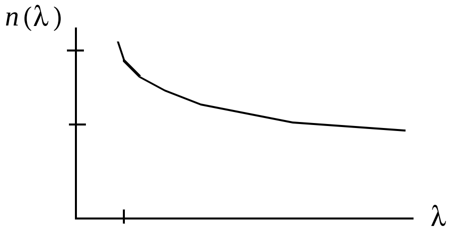
$$\boxed{\nu = \frac{c}{n} = \lambda f}$$

  Usually $n \geq 1$. (It can be < 1)

- The reason is that the electric field shakes the electrons, which tends to drag the field.
- Plane wave still has the same form: $\vec{E} = E\hat{x}\cos\left(\frac{2\pi}{\lambda}z - 2\pi ft\right)$, but the effective wavelength becomes modified by n. If we define the vacuum wavelength. $\lambda_{\mathrm{vac}} = \frac{c}{f}$ then in the material $\lambda = \frac{c}{nf} = \frac{\lambda_{\mathrm{vac}}}{n}$. The wavelength becomes <u>shorter</u>, if $n > 1$.

Dispersion

The index of refraction in most materials depends on wavelength. $n(\lambda)$. This is called dispersion.



In air – the index depends also on air pressure, humidity, and temperature which leads to many beautiful atmospheric effects.

Wavelength units (length)

We commonly use Angstrom units (Å) for light wavelength.

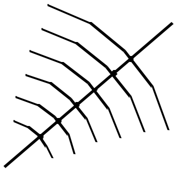
$$\boxed{1\text{Å} = 10^{-8}\text{cm} = 0.1\text{nm}}$$

This is of the order of the size of an atom. We also use standard metric units: m, cm, mm, nm

Visible light $\sim 4000 \rightarrow 7000 \mathrm{A}^{\circ}$, 400 → 700 nm, 0.4 → 0.7 μm

Spherical Waves

Another type of ideal light wave.Constant phase fronts are circular, emanating from a point source. Far away from the source, the radius of the circle becomes so large that we can approximate the wave as a plane wave.



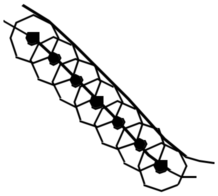
For spherical waves, we have

$$\boxed{E = E_{\circ}\frac{\cos\left(\frac{2\pi}{\lambda}r - 2\pi f t\right)}{r}}$$

Huygens' Principle

Very useful model for wave propagation.

- Every point on a wavefront is regarded as a secondary point source generating a spherical wavelet.
- The advance of the wave front is found at the envelope of all these wavelets

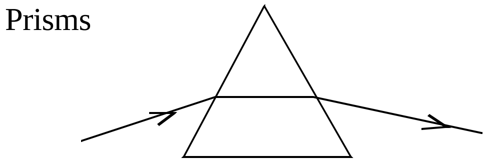


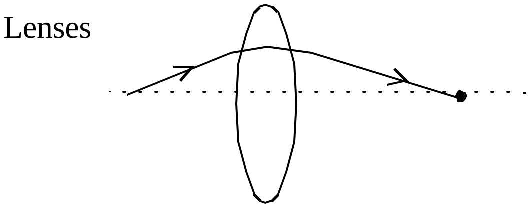
- Generally, this seems to give parallel wavefronts. But things get interesting at edges. This leads to diffraction (more later).

Rays

- Follow a point on the wavefront. As the wavefront advances the point traces a straight line. This is a ray of light.

- For many cases, we can forget the waves and just trace rays in optical systems. This allows a vast simplification of our analysis and design processes. Virtually all optical design is done with rays. Highly sophisticated optical design CAD programs are available for ray tracing.





Photons (light "particles")

- This picture has light represented by tiny bundles of energy (or quanta), following straight line paths along the rays.
- The coexistence of electromagnetic wave physics and photon physics is the central paradox of quantum mechanics.
- Each photon has an energy given by

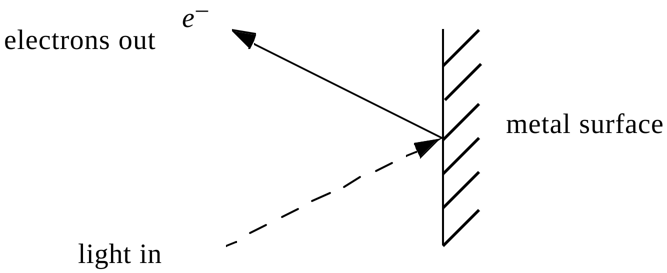
$$\boxed{\begin{array}{l} E = h\nu \\ \text{h} = 6.62\times 10^{-34}\ \text{J-s} \\ 1\,W = \ 1\text{J per second} \end{array}}$$

h is Planck's constant

For $2eV$ visible photons, $$\boxed{\begin{aligned} 1W &= 6.3\times 10^{18} eV/s \\ &= 3.15\times 10^{18}\ \text{photons/sec} \end{aligned}}$$

- Light power → photons/sec

Photoelectric Effect

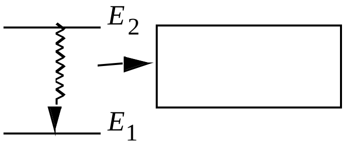


- The electron energy is directly related to the photon energy.

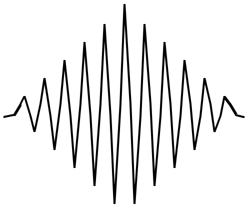
- When the photon energy is below threshold value, no electrons are emitted . The threshold depends on the metal. It is called the work function.
- When the light power is low $\sim 10^2 \rightarrow 10^3$ photons/sec → each individual electron can be separated and counted. This called <u>photon counting</u> (more later).

Atomic Radiation

- Atoms have energy states corresponding to electron orbits.



- One atom "jumps" from a higher energy state to a lower energy state and emits one <u>photon</u>.
- Photons are not point particles. They have a wave-like property. A useful picture is the wave-packet.



Many photon packets can be thought of as superimposing to make up a plane wave, spherical wave or any other wave.

The typical photon energy unit is the electron-Volt. This is defined as the energy required to push one electron across a one-Volt potential,

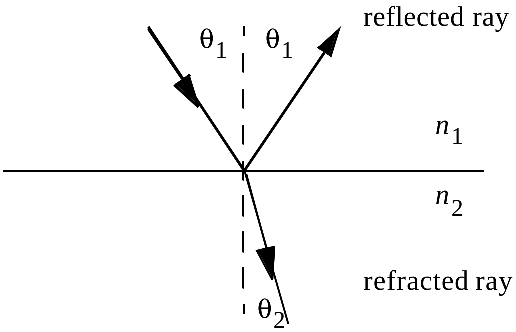
$$1\,eV = 1.6 \times 10^{-19} J$$

Typical visible photon energy ~ 1.2 → 2.3 eV

Reflection and Refraction, Snell's Law

[Reading assignment: Hecht 4.3, 4.4, 4.7]

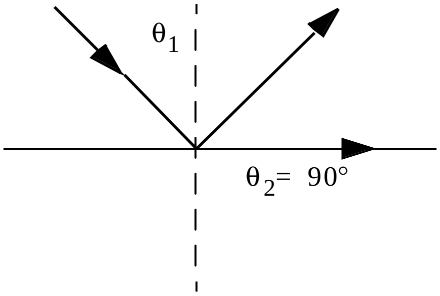
An important element of optics is the interface between 2 materials with different index of refraction



$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} \rightarrow \begin{array}{ll} \text{if } n_2 > n_1 & \theta_2 < \theta_1 \\ \text{if } n_1 > n_2 & \theta_2 > \theta_1 \end{array}$$

Total Reflection

If $n_1 > n_2$, then we can have

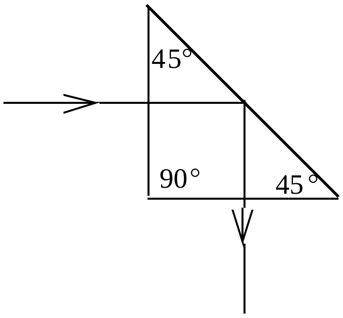


$$\theta_2 = 90^\circ$$
$$\sin\theta_c = \frac{n_2}{n_1}$$
$$\theta_c = \sin^{-1}(n_2/n_1)$$

The refracted ray disappears! The light is totally reflected. This usually occurs inside a prism , and is called total internal reflection. θ_c = “critical angle”. For a typical glass with $n = 1.5$, the critical angle is:

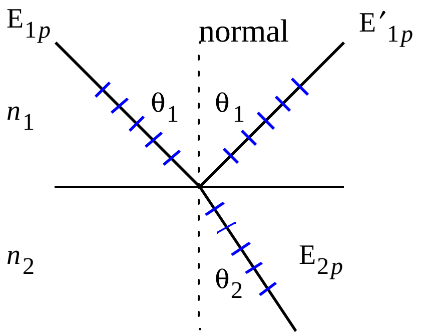
$$\boxed{\qquad\qquad\qquad}\,.$$

So for $\theta = 45^\circ$, the light is reflected. A very common prism is the right angle prism

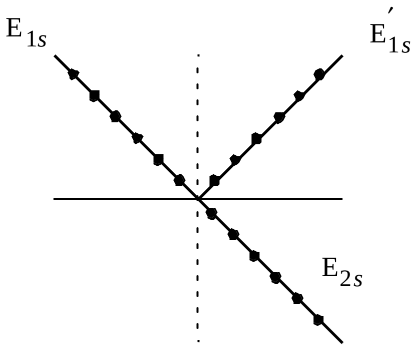


Light Impinging at a Surface

The plane containing the light ray propagation vector and the surface normal is called the "<u>plane of incidence</u>"



p-polarization
(parallel to plane of incidence)



s-polarization

- For a general polarization state incident on a surface, we choose s and p directions to decompose the polarization effects.

Fresnel Reflection Coefficients

[Optional reading: Hecht 4.6]

The magnitude of reflection and transmission at an interface between n_1 and n_2 are given by

$$R_p = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \qquad T_p = \frac{n_2\cos\theta_2}{n_1\cos\theta_1}\,\frac{4\sin^2\theta_2\cos^2\theta_1}{\sin^2(\theta_1 + \theta_2)\cos^2(\theta_1 - \theta_2)}$$

$$R_s = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} \qquad T_s = \frac{n_2\cos\theta_2}{n_1\cos\theta_1}\,\frac{4\sin^2\theta_2\cos^2\theta_1}{\sin^2(\theta_1 + \theta_2)}$$

near $\theta_1 = 0$, $R_s = R_p = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$. Notice also, if

$\theta_2 + \theta_1 = \frac{\pi}{2}$, then $\tan \to \infty$, and $R_p \to 0$.

θ_1 can be shown to be given by . This angle is known as "Brewster's angle" or the "Polarizing angle".

Polarization

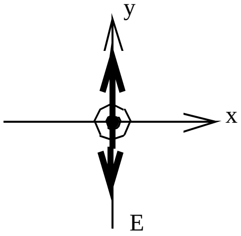
Reading Assignment: Hecht 8.1, 8.2]

- Light waves have <u>transverse</u> polarization

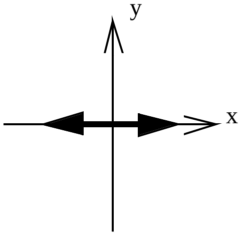
- The electric field vector points in a direction perpendicular to the propagation direction (ray direction).
- The magnetic field vector is orthogonal to propagation direction. Generally, we can ignore the magnetic field.
- The e-field vector can lie <u>anywhere</u> in transverse plane

Polarization State

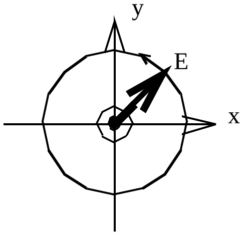
- The e-field oscillates in time at a given point in space
- For light wave propagating in z-direction, let’s look in the x-y plane.



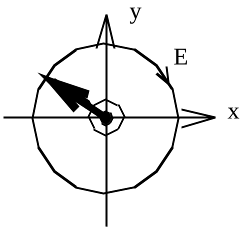
linear polarization
y-direction



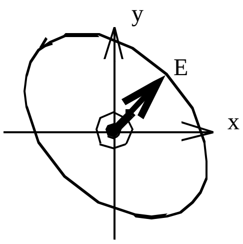
linear polarization
x-direction



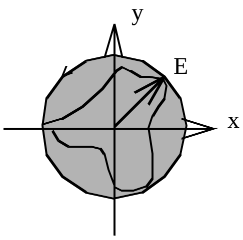
right circular
polarization



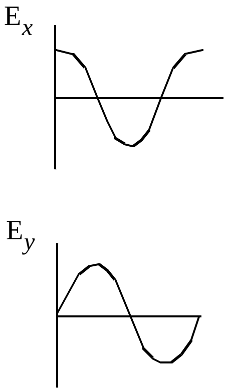
left circular
polarization



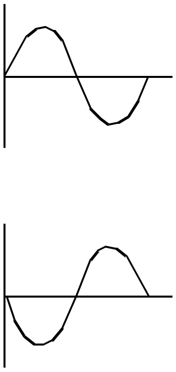
elliptical
polarization



unpolarized
(polarization-vector)
fluctuates randomly



Circular



Linear, 45°

Polarizers are devices which select one polarization

- Polarizing sheet has an allowed direction
  - transmits polarization component of incident light along the allowed direction
  - transmitted light is linearly polarized
- polarizing beamsplitter

(can be used to analyze input polarization state)