Lecture 1
Basic Properties of Light

Light is described using 3 pictures - seemingly contradictory!

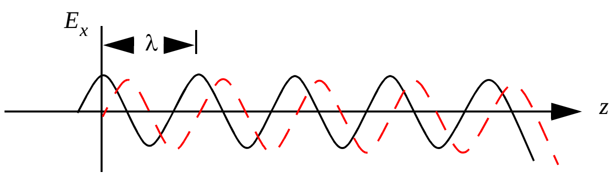
Waves - Rays - Photons

Waves

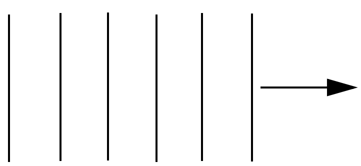
[Reading Assignment: Hecht, Chapter 2 (most of this should be review), 3.2, 3.3, 3.4.4, 3.5, 3.6]

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

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



- 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 v = distance/time $= \lambda f$. One of the many remarkable properties of light is it's universal, constant speed:

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

- 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:

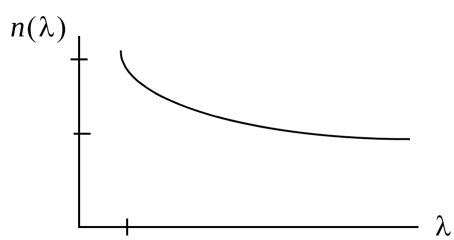
$$\nu = \frac{c}{n} = \lambda f$$

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. $\lambda_{vac} = \frac{c}{f}$ then in the material $\lambda = \frac{c}{nf} = \frac{\lambda_{vac}}{n}$. The wavelength becomes shorter, 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.

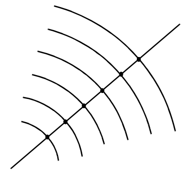
$$1\text{Å} = 10^{-8}\text{cm} = 0.1\text{nm}$$

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

Visible light $\sim 4000 \rightarrow 7000\,\text{A}^\circ$, 400 $\rightarrow$ 700 nm, 0.4 $\rightarrow$ 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.



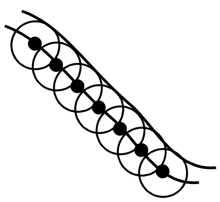
For spherical waves, we have

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

Huygens' Principle

Very useful model for wave propagation.

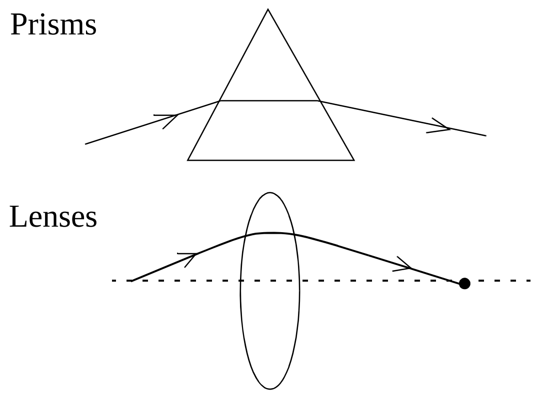
- Every point on a wavefront is regarded as a secondary point source generating a spherical wavelet.
- The advance of the wave front is found at the envelope of all these wavelets



- 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

$$E = h\nu$$

$$h = 6.62 \times 10^{-34} \text{ J-s}$$

$$1W = 1\text{J per second}$$

h is Planck's constant

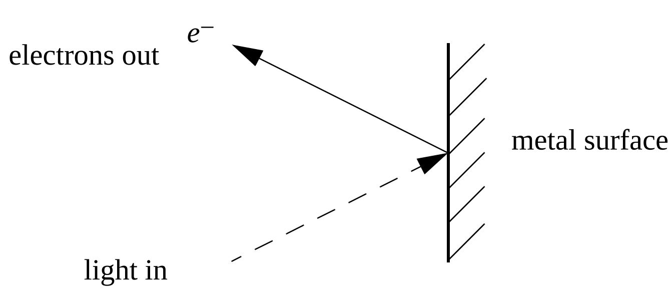
For $2eV$ visible photons,

$$1W = 6.3 \times 10^{18} eV/s$$

$$= 3.15 \times 10^{18} \text{ photons/sec}$$

- Light power $\rightarrow$ photons/sec

Photoelectric Effect

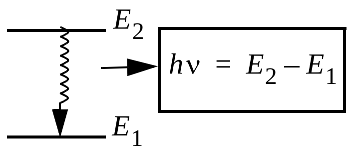


- The electron energy is directly related to the photon energy.
- When the photon energy is below threshold value, no electrons are emitted . The threshold depends on the metal. It is called the work function.

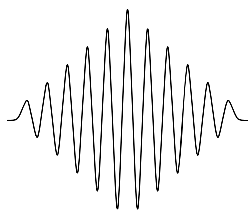
- When the light power is low $\sim 10^2 \rightarrow 10^3$ photons/sec $\rightarrow$ each individual electron can be separated and counted. This called photon counting (more later).

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 photon.
- 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,

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

Typical visible photon energy ~ $1.2 \rightarrow 2.3\ eV$