CHECKLIST

- Electromagnetic waves - all electromagnetic waves propagate in vacuum at exactly the speed of light.
  
  speed of light \( c = 2.997 \times 10^8 \text{ m.s}^{-1} \)
  
  Planck’s constant \( h = 6.626 \times 10^{-34} \text{ J.s} \)
  
  Energy quanta, photons \( E = h f \)

- Atoms and light, scattering and absorption (page 895 – 897)
  
  Electromagnetic spectrum (pages 897 – 906)
    - radio
    - microwaves
    - IR
    - visible
    - UV
    - X-rays
    - gamma rays

- Refraction – bending of wavefronts due to a change in speed of the wave (Fig. 23.24 only, page 927) Refractive index \( n = c / v \) (23.2)

- Snell's Law – Law of Refraction
  \[
  n_1 \sin \theta_1 = n_2 \sin \theta_2
  \]

- Thin-film interference (Section 25.5 pages 1011 – 1015): interference, optical path length, fringes, maxima (constructive interference) & minima (destructive interference)
  
  The phase difference between the two waves is
  \[
  \Delta \phi = 2\pi \left( \frac{2d}{\lambda_f} \right) + \phi_1 + \phi_2 = 2\pi \left( \frac{2d n_f}{\lambda_0} \right) + \phi_1 + \phi_2
  \]

  The \( \phi \)'s are determined from the reflections at the interfaces. Remember a pulse traveling down a thin string is reflected with a phase shift of \( \pi \text{ rad} \) (inverted) at the interface with a heavy string. So a reflected light wave has a \( \pi \) change of phase when it is incident upon a material that has a greater refractive index (optically more dense).

  For constructive interference \( \Delta \phi = m (2\pi) \text{ rad} \)

  \( m = 0, 1, 2, 3, \ldots \)

  For destructive interference \( \Delta \phi = (2m+1)(\pi) \text{ rad} \)
NOTES

A **progressive electromagnetic wave** is a self-supporting, energy-carrying disturbance that travels free of its source. The light from the Sun travels through space (no medium) for only 8.3 minutes before arriving at Earth. Each form of electromagnetic radiation (radiowaves, microwaves, infrared, light, ultraviolet, x-rays and γ rays) is a web of oscillating electric and magnetic fields inducing one another. A fluctuating electric field (electric charges experience forces) creates a magnetic field (moving charges experience forces) perpendicular to itself, surrounding and extending beyond it. That magnetic field sweeping off to a point further in space is varying there, and so generates a perpendicular electric fields that spreads out . . . . Nothing is actually displaced in space like a water wave where the water oscillates up and down and side-ways.

All electromagnetic waves propagate in vacuum at exactly

\[ c = 2.997 \, 924 \, 85 \, \text{m.s}^{-1} \]

This is a tremendous speed, light travels 1m in only \( 3.3 \times 10^{10} \) s.

"There are only two fundamental mechanisms for transporting energy and momentum: a streaming of particles and a flowing of waves. And even these two seemingly opposite conceptions are subtly intertwined – there are no waves without particles and no particles without waves … " from Hecht.

The particles associated with electromagnetic waves are called **photons**. The energy of a single photon is

\[ E = h f \]

\[ E \quad \text{energy of photon (J)} \quad \text{electron volt} \quad 1 \, \text{eV} = 1.6 \times 10^{-19} \, \text{J} \]

\[ f \quad \text{frequency of electromagnetic wave (Hz)} \]

\[ h \quad \text{Planck's constant (J.s)} \quad \text{-a fundamental constant of nature} \]

\[ h = 6.626 \times 10^{-34} \, \text{J.s} \]

The emission and absorption of light (transfer of energy & momentum) takes place in a particle manner. All forms of electromagnetic radiation, interact with matter in the process of emission and absorption. The radiation propagates in a wavelike fashion but in an interaction the radiation behaves as a concentration of energy (photons) moving at the speed of light.

Each photon carries very little energy. However, even an ordinary torch beam is a torrent of \(~10^{17}\) photons.s\(^{-1}\). When we “see” light what we observe by eye or on film is the average energy per unit area per time arriving at some surface.
ATOMS and LIGHT

Most of the chemical and optical properties of a substance are dependent upon the outermost bound electrons in atoms. Each electron is usually in its **ground state** – the lowest energy state. Only when an atom absorbs specific and sufficient energy can the atom move to a well-defined higher energy state (**excited state**).

**Resonant Absorption**

\[ h f = E_2 - E_1 \]

\[ h f \neq E_2 - E_1 \]
Spontaneous emission

\[ h \nu = E_2 - E_1 \]

Scattering process - an atom absorbs a photon and emits another photon e.g., transmission of light through a glass window pane, reflection of a face from a mirror, red sunsets.

Non-resonant scattering – incident photons do not cause quantum jumps but instead the energy is absorbed which results in the atom's electron cloud vibrating at the frequency of the incident radiation. The vibrating atoms act as tiny sources and emit radiation in all directions.

Resonant absorption – incident photon energy matches the energy difference between two states, \( h \nu = \Delta E \) and causes the atom to "jump" to a higher excited state.

Dissipative absorption – in solids and liquids many atoms "clump" together. Excited atoms lose their energy by collisions rather than emitting photons. Through collisions with nearest neighbours the energy is dissipated into the random kinetic energy of the atoms. Most things have colour because of selective dissipative absorption. Your skin under white light illumination selective dissipates energy by absorption at certain frequencies and scatters others giving is colour.
## ELECTROMAGNETIC SPECTRUM

<table>
<thead>
<tr>
<th>Radiation</th>
<th>f (Hz)</th>
<th>( \lambda ) (m)</th>
<th>Photon Energy (eV)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>power lines</td>
<td>50</td>
<td>( 6 \times 10^6 )</td>
<td>( 2 \times 10^{-13} )</td>
<td>Currents. Radiation emitted from 50 Hz power lines – are they dangerous?</td>
</tr>
<tr>
<td>radio AM FM TV</td>
<td>&lt; ( 10^9 )</td>
<td>&gt; 0.3</td>
<td>&lt; ( 4 \times 10^{-6} )</td>
<td>Currents, electronic circuits. AM FM radio, TV.</td>
</tr>
<tr>
<td>microwaves</td>
<td>( 10^9 )</td>
<td>0.3</td>
<td>( 4 \times 10^{-6} )</td>
<td>Magnetron. ( \lambda \sim 10 ) mm to 30 m can penetrate atmosphere – satellite communications, mobile phones, police radar, microwave cooking (polar water molecule), medical – diathermy.</td>
</tr>
<tr>
<td>infrared</td>
<td>( 3 \times 10^{11} )</td>
<td>( 1 \times 10^{-3} )</td>
<td>( 1 \times 10^{-3} )</td>
<td>Molecular vibrations &amp; rotations, all objects. Why do you get warm standing in the sun? Thermography, IR satellite images, detecting tumors &amp; cancers.</td>
</tr>
<tr>
<td>light</td>
<td>( 3.9 \times 10^{14} )</td>
<td>( 7.8 \times 10^{-7} )</td>
<td>2</td>
<td>Outer electrons, incandescent lamps, lasers, arcs. Eye sensitive to this narrow band. White light mixture of all colours of visible spectrum. TV (red blue green). If a an uranium atom enlarged to a size of a pea, ( \lambda_{\text{red}} \sim 20 ) m long. Sunlight ( \sim 10^{17} ) photons.s(^{-1}).m(^{-2}). Blue light photons sufficient energy to disrupt chemical bonds.</td>
</tr>
<tr>
<td>ultraviolet</td>
<td>( 8 \times 10^{-14} )</td>
<td>( 4 \times 10^{-7} )</td>
<td>3</td>
<td>Inner &amp; outer electrons. Ionising (4 eV photons break C-C bonds). Skin cancers, tans the skin, vitamin D synthesis, damage to eyes. O(_3) layer absorbs UV – protection layer. Can kill micro-organisms.</td>
</tr>
<tr>
<td>x-rays</td>
<td>( 3 \times 10^{16} )</td>
<td>( 1 \times 10^{-8} )</td>
<td>( 1 \times 10^{2} )</td>
<td>Inner electrons, x-ray tubes. Diagnostic medical-rays.Computed tomography CT scan. Crystal &amp; molecular structures.</td>
</tr>
<tr>
<td>( \gamma )-rays</td>
<td>&gt; ( 10^{18} )</td>
<td>( 3 \times 10^{-10} )</td>
<td>&gt; ( 4 \times 10^{3} )</td>
<td>Nuclei, accelerators. Sterilisation, food preservation, cancer treatment, medical diagnosis, flaw detection. Very penetrating – can pass through large thickness of concrete.</td>
</tr>
</tbody>
</table>
REFRACTION

How can we see?
What produces an image in an optical microscope?
What happens when light passes through a transparent material?

When light enters a transparent material, the photons are absorbed by the molecules. The atoms are set vibrating and new photons are emitted. The absorption and emission of photons, result in a change of speed of light through the material. The change in speed can depend upon the frequency of the incident radiation. This is called dispersion – it is responsible for the separation of white light into its constituent colours by a prism.

![Dispersion Image](image)

The ratio of the speed of an electromagnetic wave, $c$ in vacuum to that in the medium, $v$ is defined as the **refractive index**, $n$

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

When a wave enters a new medium (different wave speed) at an angle the wavefront must bend. This bending is called refraction. The amount of bending is described by **Snell’s Law (Law of Refraction)**

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

- When light enters the eye, most of the light is bent at the cornea and fine adjusts by the lens to focus the light onto the retina. Glasses correct for eye defects to produce a focussed image.
- In a transmission optical microscope light passes through a sample and the path of the light is bend by the various lens. The image gives a "map" of the refractive index variation throughout the sample.
- Fiberoptics – bending of light through a glass fibre.
- $n_1 > n_2$, light bent away from normal.
- $n_1 < n_2$, light bent towards normal.
THIN FILM INTERFERENCE

Thin films are responsible for colours of soap bubbles, oil sticks, iridescence of peacock feathers, blooming of camera lenses ….

When light impinges on the first surface of a transparent film, a portion of the incident wave is partially reflected and partially transmitted. The transmitted portion is then reflected from a second surface and emerges back out of the film. Thus, emerging from the thin film are two waves (1) wave reflected from front surface and (2) wave reflected from rear surface. The two waves have different path optical lengths that is determined by the width of the film. The two waves will eventually interfere and the interference pattern observed will depend upon the thickness of the film.

Consider a thin oil film with varying thickness. Whenever the film is exactly the right thickness for the two waves of emerging red light to undergo constructive interference, the film will appear red at this location and the same for the other colours for different thicknesses in different locations. Thus, the oil film will show its characteristic with multi-coloured fringe pattern when viewed under white light.

Images: http://hypertextbook.com/physics/waves/thin-films/
The reflected wave from the rear surface travels an extra distance $2d$ (path difference) before it is superimposed and interferes with the wave reflected from the front surface.

The wavelength $\lambda_f$ of the wave in the film is different from that in a vacuum $\lambda_o$

$$\lambda_f = \frac{\lambda_o}{n_f}$$

The optical path length is ($2d$) $n_f$

The phase difference between the two waves is

$$\Delta \phi = 2\pi \left( \frac{2d}{\lambda_f} \right) + \phi_1 + \phi_2 = 2\pi \left( \frac{2d n_f}{\lambda_o} \right) + \phi_1 + \phi_2$$

The $\phi$'s are determined from the reflections at the interfaces. Remember a pulse travelling down a thin string is reflected with a phase shift of $\pi$ rad (inverted) at the interface with a heavy string. So a reflected light wave has a $\pi$ change of phase when it is incident upon a material that has a greater refractive index (optically more dense).

For constructive interference $\Delta \phi = m (2\pi)$ rad 

$m = 0, 1, 2, 3, \ldots$

For destructive interference $\Delta \phi = (2m+1)(\pi)$ rad

Thin film destructive interference is the principle behind coating optical surfaces such as lenses to reduce reflections so more light then can be transmitted. An uncoated air-
glass interface reflects ~ 4% of the incident light. In a multiple lens system, the loss of transmitted light can be significant. Often lens are coated with magnetism fluoride to reduce reflections to produce a gain in the transmission of the lens system.

For thick films it becomes possible for many different colours to have their maxima at the same locations. Where many wavelengths can interfere constructively at the same time, the reflected colour becomes increasing unsaturated and the fringe contrast disappears.

Why is the feather coloured? The ring and other highlights around the neck of the pigeon are the result of destructive interference, not pigmentation.

**Problem**
Light is incident normally on a thin film with an index of reflection \( n_f = 1.35 \). The film covers a glass lens of refractive index 1.5. What is the minimum thickness of the film to minimise the reflection of red light (633 nm)?

**Solution**

\[
\begin{align*}
    n_1 &= 1 \\
    n_f &= 1.35 \\
    n_2 &= 1.5 \\
    \lambda_0 &= 633 \text{ nm} = 633 \times 10^{-9} \text{ m}
\end{align*}
\]

To minimise reflections we need the reflected waves to interfere destructively.

\[
\begin{align*}
    \Delta \phi &= 2\pi \left( \frac{2d n_f}{\lambda_0} \right) + \phi_1 + \phi_2 = \pi \text{ rad} \\
    \text{reflection at front interface} \quad n_1 < n_f &\Rightarrow \phi_1 = \pi \\
    \text{reflection at rear interface} \quad n_f < n_2 &\Rightarrow \phi_2 = \pi
\end{align*}
\]

\[
\phi_1 + \phi_2 = 2\pi \Rightarrow \text{can ignore the total phase change due to interface reflections}
\]

\[
\begin{align*}
    \Delta \phi &= 2\pi \left( \frac{2d n_f}{\lambda_0} \right) = \pi \text{ rad}
\end{align*}
\]

\[
\begin{align*}
    d &= \frac{\lambda_0}{4n_f} = \frac{633 \times 10^{-9}}{(1.35)(4)} = 1.17 \times 10^{-7} \text{ m} = 117 \text{ nm}
\end{align*}
\]

Reference:
http://www.nebhe.org/photonIIsite/interference_defraction.pdf