Chapter 4. The Properties of Light

4.1 Introduction
Scattering $\rightarrow$ Transmission, reflection, and refraction
(microscopic) $\rightarrow$ (macroscopic)

4.2 Rayleigh Scattering
• Scattering of sunlight
  Sunlight in the air $\rightarrow$ Ground-state vibration of nitrogen, oxygen, etc.
  Higher freq. of light $\rightarrow$ Larger amplitude of ground-state vibration.
  Stronger scattering.

The intensity of the scattered light $\sim \nu^4$
Blue scatters more strongly than red (Blue sky)

Rayleigh scattering $\overset{\text{def}}{=} \text{Scattering from particles } < \lambda/15$

A. Scattering and Interference
• Rare medium (separation $\geq \lambda$).
  $\rightarrow$ Optical path difference to $P >> \lambda$.
  $\rightarrow$ Intensities are added at $P$

• The dense medium (separation $\leq \lambda$).
  $\rightarrow$ Electric fields are added at $P$.
  $\rightarrow$ Less lateral scattering due to interference.
Forward Propagation
The same optical path length to $P$
$\rightarrow$ Constructive interference in forward direction.

B. The Transmission of Light Through Dense Media
Little scatterings in the lateral or the backward directions

A fixed phase difference among wavelets in the lateral direction.
$\rightarrow$ Sumed to zero

More dense, uniform and ordered medium
$\rightarrow$ More complete lateral destructive interference
$\rightarrow$ Forward propagation without diminish

Example
Glass, plastic : amorphous solids $\rightarrow$ Lateral scattering
Quartz, mica : crystals $\rightarrow$ Smaller lateral scattering
C. Transmission and the Index of Refraction

A primary wave in a dielectric.

→ Ground-state vibrations of atoms
→ Spherical wavelets
→ Interference of wavelets to form secondary wave.

The primary + The secondary wave ⇒ The transmitted wave

↑

Same speed of \( c \)

The phase velocity = \( c \), \( < c \), \( > c \).
Refraction index change.

- Primary wave → Electron oscillator → Secondary wave

\( 0 \sim \pi \) phase shift
90° phase lag, natural result
Lorentz model (3.5)

For \( \omega \ll \omega_o \) : The secondary lags the primary by 90°
For \( \omega \approx \omega_o \), at resonance : 180° out of phase. Reduced refracted wave (absorption)
For \( \omega \gg \omega_o \) : 270° phase lag

\[ Dashed: \text{ reduced damping} \]

- Accumulated phase lag or lead → Speed change of the wave.
4.3 Reflection

A beam of light in a dense medium → Scattering mostly in the forward direction
A beam of light across an interface → Some backward scattering. Reflection

The change of $n$ over a distance $> \lambda$ → Little reflection
The change of $n$ over a distance $< \lambda / 4$ → Abrupt interface

Internal and External Reflection

Unpaired atomic oscillators → Reflection
Indep. of glass thickness

Huygens’s Principle

Every point on a primary wavefront behaves as a point source of spherical secondary wavelet.
The secondary wavelets propagate with the same speed and frequency with the primary wave.
The wave at a later time is the superposition of these wavelets.

Rays

A ray is a line drawn in the direction of light propagation.
In most cases, ray is straight and perpendicular to the wavefront.
A plane wave is represented by a single ray.

A. The Law of Reflection

A plane wave into a flat medium ($\lambda >>$ atomic spacing)
→ Spherical wavelets from the atoms.
→ Constructive interference only in one direction.
Derivation of the law
At \( t=0 \), the wavefront is \( AB \)
At \( t=t_1 \), the wavefront is \( CD \)

Note
\[
\begin{align*}
v_i t_1 &= BD = AD \sin \theta_i, \\
v_r t_1 &= AC = AD \sin \theta_r \\
\frac{\sin \theta_i}{v_i} &= \frac{\sin \theta_r}{v_r}
\end{align*}
\]

Since \( v_i = v_r \)
\[
\theta_i = \theta_r
\]

: Law of reflection (Part I)

4.4 Refraction

The incident rays are bent at an interface

→ Refraction

A. The Law of Refraction
At \( t=0 \) the wavefront is \( AB \)
At \( t = \Delta t \) the wavefront is \( ED \)

\[
\begin{align*}
v_i \Delta t &= BD = AD \sin \theta_i \\
v_r \Delta t &= AC = AD \sin \theta_i \\
\frac{\sin \theta_i}{v_i} &= \frac{\sin \theta_r}{v_r}
\end{align*}
\]

Since \( v_i = \frac{c}{n_i}, \ v_r = \frac{c}{n_r} \)
\[
\begin{align*}
n_i \sin \theta_i &= n_r \sin \theta_r
\end{align*}
\]

: Law of refraction, Snell’s law

• A weak electric field
→ A linear response of the atom
→ A simple harmonic vibration of the atom
→ The frequencies of the incident, reflected and refracted waves are equal.

4.5 Fermat’s Principle

Hero proposed the principle of shortest path
\[
\theta_i = 0
\]

\( S, P \) and \( B \) are in the plane of incidence

Fermat proposed the principle of least time
→ Light takes the path that takes the least time
• **Reflection by Fermat’s principle**
  The time from $S$ to $P$
  \[ t = \frac{SO}{v_i} + \frac{DP}{v_i} = \sqrt{h^2 + x^2} \frac{v_i}{v_t} + \sqrt{b^2 + (a - x)^2} \frac{v_i}{v_t} \]
  \[ \frac{\sin \theta_i}{v_i} = \frac{\sin \theta_t}{v_t} \quad \text{Snell’s law} \]
  \[ \frac{dt}{dx} = 0 \]

• **Optical Path Length**
  The transit time from $S$ to $P$
  \[ t = \sum_{i=1}^{m} \frac{s_i}{v_i} = \frac{1}{c} \sum_{i=1}^{m} n_i s_i \]
  \[ \text{Optical path length (OPL)} \]
  In an inhomogeneous medium
  \[ OPL = \int_{S}^{P} n(s) ds \]

• **Modern Fermat’s Principle**
  The optical path length of the actual light path is stationary with respect to variations of the path
  \[ \frac{df}{dx} = 0 \]
  Not allowed in the principle of least time
  Rays slightly deviate from the stationary path
  → The same OPL
  → Constructive interference

• **Stationary paths in an ellipsoidal mirror**

• **Fermat and Mirages**
  [Fig. 4.31-33] Bending of rays due to Fermat’s principle
4.6 The Electromagnetic Approach

A. Waves at an Interface

An incident plane wave

$$\vec{E}_i = \vec{E}_{oi} \cos (\vec{k}_i \cdot \vec{r} - \omega_i t)$$

The reflected and transmitted waves

$$\vec{E}_r = \vec{E}_{or} \cos (\vec{k}_r \cdot \vec{r} - \omega_r t + \varepsilon_r)$$
$$\vec{E}_t = \vec{E}_{ot} \cos (\vec{k}_t \cdot \vec{r} - \omega_t t + \varepsilon_t)$$

$\varepsilon_i, \varepsilon_r, \varepsilon_t$ are constant phases

The boundary conditions

$$\left(\vec{E}_{it}\right)_{\text{tangential}} + \left(\vec{E}_{rt}\right)_{\text{tangential}} = \left(\vec{E}_{ri}\right)_{\text{tangential}}$$

$$\uparrow \quad \uparrow \quad \uparrow$$
$$\vec{u}_n \times \vec{E}_i \quad \vec{u}_n \times \vec{E}_r \quad \vec{u}_n \times \vec{E}_t$$

This relation should be satisfied regardless of $\vec{r}$ and $t$

$$\omega_i = \omega_r = \omega_t$$
$$\vec{k}_i \cdot \vec{r} = \vec{k}_r \cdot \vec{r} + \varepsilon_r = \vec{k}_t \cdot \vec{r} + \varepsilon_t$$

• From the first two of (1)

$$\left(\vec{k}_i - \vec{k}_r\right) \cdot \vec{r} = \varepsilon_r : \vec{r} \text{ is on the interface plane}$$

$$\left(\vec{k}_i - \vec{k}_r\right) \cdot (\vec{r} - \vec{r}_o) = 0 : \vec{r}_o \text{ is a point on the interface plane}$$

$$\left(\vec{k}_i - \vec{k}_r\right) / \vec{u}_n : \vec{u}_n \text{ is the surface normal}$$

$$\vec{k}_i, \vec{k}_r \text{ and } \vec{u}_n \text{ form a plane (Plane of incidence)}$$

$$|\vec{k}_i| \sin \theta_i = |\vec{k}_r| \sin \theta_r \quad \Rightarrow \quad \theta_i = \theta_r$$

$$|\vec{k}_i| = |\vec{k}_r|$$

From the first and last of (1)

$$\left(\vec{k}_i - \vec{k}_t\right) \cdot \vec{r} = \varepsilon_t$$

$$\left(\vec{k}_i - \vec{k}_t\right) \cdot (\vec{r} - \vec{r}_o) = 0$$

$$\left(\vec{k}_i - \vec{k}_t\right) \perp \text{The interface plane}$$

$$\vec{k}_i, \vec{k}_t \text{ and } \vec{u}_n \text{ form the plane of incidence}$$

$$|\vec{k}_i| \sin \theta_i = |\vec{k}_t| \sin \theta_t \quad \Rightarrow \quad n_i \sin \theta_i = n_t \sin \theta_t$$

$$\uparrow k = \frac{n \omega}{c}$$
B. The Fresnel Eqs.

Case 1. \( \vec{E} \perp \) The plane of incidence

The relation among \( \vec{E}, \vec{H}, \) and \( \vec{k} \)

\[
\left( \vec{E} \times \vec{H} \right) / / \vec{k}, \quad \left( \vec{k} \times \vec{E} \right) / / \vec{H}
\]

At the interface

\[
E_{oi} + E_{or} = E_{ot}
\]

\[
\left( \vec{H}_{oi} \right)_{\text{tangential}} + \left( \vec{H}_{or} \right)_{\text{tangential}} = \left( \vec{H}_{ot} \right)_{\text{tangential}}
\]

\[
-\vec{H}_{oi} \cos \theta_i \hat{x} + \vec{H}_{or} \cos \theta_r \hat{x} -\vec{H}_{ot} \cos \theta_t \hat{x}
\]

Since \( H = \vec{E} / \mu \nu \)

\[
\frac{1}{\mu_i \nu_i} (E_{oi} - E_{or}) \cos \theta_i = \frac{1}{\mu_o \nu_o} E_{ot} \cos \theta_t
\]

From (1) and (2) with \( \mu_i = \mu_r = \mu_t = \mu_o, \nu = c / n \)

**Amplitude reflection coefficient**

\[
\left\{ \frac{E_{or}}{E_{oi}} \right\}_i = -\frac{n_t \cos \theta_i - n_i \cos \theta_i}{n_i \cos \theta_i + n_t \cos \theta_i} = r_i
\]

**Amplitude transmission coefficient**

\[
\left\{ \frac{E_{ot}}{E_{oi}} \right\}_i = \frac{2n_t \cos \theta_i}{n_i \cos \theta_i + n_t \cos \theta_i} = t_i
\]

The physical meaning of a phase shift in the reflected wave when \( n_t > n_i \).
**Case 2.**  

The plane of incidence

\[ \vec{E}_{\text{tangential}} \] should be continuous across the interface

\[
\begin{align*}
\vec{E}_{\text{tangential}}^{\text{in}} + \vec{E}_{\text{tangential}}^{\text{out}} &= \vec{E}_{\text{tangential}}^{\text{in}} + \vec{E}_{\text{tangential}}^{\text{out}} \\
E_{\text{in}} \cos \theta_i \hat{x}, & -E_{\text{out}} \cos \theta_r \hat{x}, & E_{\text{out}} \cos \theta_i \hat{x}, & : \vec{E} \text{ is such that } \vec{B} \text{ points outward}
\end{align*}
\]

\[ (3) \]

\[ \vec{H}_{\text{tangential}} \] should be continuous across the interface

\[
\begin{align*}
\vec{H}_{\text{tangential}}^{\text{in}} + \vec{H}_{\text{tangential}}^{\text{out}} &= \vec{H}_{\text{tangential}}^{\text{in}} + \vec{H}_{\text{tangential}}^{\text{out}} \\
\frac{1}{\mu_i \nu_i} \vec{E}_{\text{in}} \hat{z} + \frac{1}{\mu_r \nu_r} \vec{E}_{\text{out}} \hat{z} + \frac{1}{\mu_i \nu_i} \vec{E}_{\text{out}} \hat{z}
\end{align*}
\]

\[ (4) \]

From (3) and (4) with \( \theta_i = \theta_r \), \( \nu_i = \nu_r \), \( \mu_i = \mu_r = \mu_\perp = \mu_\parallel \), \( \nu = c / n \)

**Amplitude reflection coefficient**

\[
\begin{align*}
\frac{E_{\text{in}}}{E_{\text{in}}} &= n_i \cos \theta_i - n_i \cos \theta_r \\
&= \frac{n_i \cos \theta_i}{n_i \cos \theta_i + n_i \cos \theta_r} = r_i
\end{align*}
\]

**Amplitude transmission coefficient**

\[
\begin{align*}
\frac{E_{\text{in}}}{E_{\text{in}}} &= \frac{2n_i \cos \theta_i}{n_i \cos \theta_i + n_i \cos \theta_r} = t_i
\end{align*}
\]

**•** Applying Snell’s law assuming \( \theta_i \neq 0 \), Fresnel Eqs. become

\[
\begin{align*}
r_i &= \frac{\sin (\theta_i - \theta_r)}{\sin (\theta_i + \theta_r)} \\
t_i &= \frac{2 \sin \theta_i \cos \theta_i}{\sin (\theta_i + \theta_r)} \\
t_i &= \frac{\tan (\theta_i - \theta_r)}{\tan (\theta_i + \theta_r)} \\
t_i &= \frac{2 \sin \theta_i \cos \theta_i}{\sin (\theta_i + \theta_r) \cos (\theta_i - \theta_r)}
\end{align*}
\]
C. Interpretation of the Fresnel Eqs.

**Amplitude Coefficients**

At normal incidence, $\theta_i = 0$

$$|r| = |t| = \frac{n_t - n_i}{n_t + n_i}$$

- The external reflection ($n_i > n_t, \ \theta_i > \theta_t$)
  
  $r_\perp < 0$, $r_\| = 0$ when $(\theta_i + \theta_t) = 90^\circ$: *Brewster angle, Polarization angle* of $\theta_i = \theta_p$.

- The internal reflection ($n_i > n_t, \ \theta_i > \theta_t$)
  
  $r_\perp = 1$ when $\theta_i = 90^\circ$, $r_\| = 0$ when $(\theta_i + \theta_t) = 90^\circ$: *Critical angle* of $\theta_i = 0$ in $n_i \sin \theta_i = n_t$.

\[ n_i > n_t, \ n_t = 1.5 \]

Stronger reflection at glancing angle

\[ n_i > n_t, \ n_i = 1.5 \]

Reflectance and Transmittance

The power per unit area : $S = \mathbf{E} \times \mathbf{H}$, **poynting vector**

In phasor form : $\tilde{S} = \frac{1}{2} \left( \mathbf{E} \times \mathbf{H}^* \right)$

The **intensity** ($W/m^2$) : **Irradiance**

$$I = \langle S \rangle = \frac{1}{2} \frac{c}{n} \varepsilon_0 \varepsilon_r E_0^2$$

: Average energy per unit time per unit area
The cross sectional area of the incident beam \( A_i \cos \theta_i \) equals the area of the reflected beam \( A_r \cos \theta_r \) and the transmitted beam \( A_t \cos \theta_t \).

The **reflectance**

\[
R = \frac{\text{Reflected power}}{\text{Incident power}} = \frac{I_r A \cos \theta_r}{I_i A \cos \theta_i} \Rightarrow \frac{I_r}{I_i} = \left| \frac{E_{oi}}{E_{oi}} \right|^2 = r^2
\]

The **transmittance**

\[
T = \frac{\text{Transmitted power}}{\text{Incident power}} = \frac{I_t A \cos \theta_t}{I_i A \cos \theta_i} \Rightarrow \frac{E_{ot}}{E_{oi}} = \left( \frac{n_i \cos \theta_i}{n_t \cos \theta_t} \right)
\]

- **Energy conservation**

\[
I_i A \cos \theta_i = I_r A \cos \theta_r + I_t A \cos \theta_t
\]

\[
\rightarrow n_i E_{oi}^2 \cos \theta_i = n_r E_{or}^2 \cos \theta_r + n_t E_{ot}^2 \cos \theta_t
\]

\[
\rightarrow 1 = \left( \frac{E_{or}}{E_{oi}} \right)^2 + \left( \frac{n_i \cos \theta_i}{n_t \cos \theta_t} \right) \left( \frac{E_{ot}}{E_{oi}} \right)^2
\]

\[
\uparrow R \quad \uparrow T
\]
4.7 Total Internal reflection

The Snell’s law for $n_i > n_t$

$$\sin \theta_i = \frac{n_t}{n_i} \sin \theta_t \quad : \theta_i < \theta_t$$

At the critical angle, $\theta_t = 90^\circ$

$$\sin \theta_c = \frac{n_t}{n_i}$$

For $\theta_i > \theta_c$

$\rightarrow$ All the incoming energy is reflected back into the incident medium

*Total Internal Reflection*

Internal reflection and TIR:
Transition from (a) to (e) without discontinuity.
(Reflection increases while transmission decreases)

TIR in prisms
The critical angle at air-glass interface : $42^\circ$

TIR in terms of scattering

A surface wave when $\theta_c = 90^\circ$
A. The Evanescent Wave

Using Snell’s law we rewrite Fresnel Eq. as

\[
 r_\perp = \frac{n_i \cos \theta_i - n_t \cos \theta_t}{n_i \cos \theta_i + n_t \cos \theta_t} \Rightarrow \sqrt{\left(\frac{n_i}{n_t}\right)^2 - \sin^2 \theta_i - \cos \theta_i} \sqrt{\left(\frac{n_i}{n_t}\right)^2 - \sin^2 \theta_i + \cos \theta_i}
\]

\[
 r_\parallel = \frac{-n_i \cos \theta_i - n_t \cos \theta_t}{n_i \cos \theta_i + n_t \cos \theta_t} \Rightarrow \sqrt{\left(\frac{n_i}{n_t}\right)^2 - \sin^2 \theta_i - (n_i/n_t)^2 \cos \theta_i} \sqrt{\left(\frac{n_i}{n_t}\right)^2 - \sin^2 \theta_i + (n_i/n_t)^2 \cos \theta_i}
\]

\[r_\perp, \ r_\parallel\] become complex when \( \theta_i > \theta_c \)

\[\rightarrow \quad r_\perp r_\perp^* = r_\parallel r_\parallel^* = R = 1\]

- The transmitted wave: \( \vec{E}_t = E_{\text{om}} e^{i(k_z x + k_y y)} \) where \( \vec{k}_t = k_{tx} \hat{x} + k_{ty} \hat{y} \)

\[k_{tx} = k_i \sin \theta_i \Rightarrow \frac{n_i}{n_t} \sin \theta_i \]

\[k_{ty} = k_i \cos \theta_i \Rightarrow \pm k_i \sqrt{1 - \left(\frac{n_i}{n_t}\right)^2} \sin \theta_i \Rightarrow \pm i \left[ k_t \sqrt{\left(\frac{n_i}{n_t}\right)^2} \sin \theta_i - 1 \right] \]

\[\uparrow \quad \uparrow \quad \uparrow = \beta \quad \quad \theta_i > \theta_c \]

The transmitted wave: \( \vec{E}_t = \vec{E}_{\text{om}} e^{i\beta_x x + i\beta_y y} \), Evanescent wave

\[\rightarrow \quad \text{It advances in x-direction but exponential decay along y-axis} \]

\[\rightarrow \quad \text{Constant phase (yz-plane)} \quad \perp \quad \text{Constant amplitude (xz-plane), Inhomogeneous wave} \]

\[\text{No net energy flow across the interface.}\]

- **Frustrated Total Internal Reflection (FTIR)**

  Dense medium \( \rightarrow \) Rare medium \( \rightarrow \) Dense medium (Energy transfer)

  \[\uparrow \quad \uparrow \quad \uparrow \quad \text{TIR} \quad \text{Evanescent wave}\]

[Fig. 4.55] FTIR
[Fig. 4.56] Beamsplitter using FTIR

Low-index space controls the transmittance
4.8 Optical Properties of Metals

Free electrons in metals $\mathbf{\rightarrow} \quad \mathbf{J} = \sigma \mathbf{E}$

$\uparrow$ Unbound $\uparrow \uparrow$ Conductivity $\uparrow \uparrow$ Current density

A perfect conductor: $\sigma = \infty$
$\rightarrow$ Electrons follow the electric field exactly
(No restoring force, no natural freq., no absorption, only reemission)

In real metals: $\sigma \neq \infty$
Collision of electrons with lattice or imperfections
$\rightarrow$ Energy loss by heat

Waves in a metal
The Maxwell’s eqs. in metals

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \times \mathbf{H} = \epsilon \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E}$$

$$\frac{\partial^2 \mathbf{E}}{\partial x^2} + \frac{\partial^2 \mathbf{E}}{\partial y^2} + \frac{\partial^2 \mathbf{E}}{\partial z^2} = \mu \epsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} + \mu \sigma \frac{\partial \mathbf{E}}{\partial t} \Rightarrow -\omega^2 \mu \epsilon \sigma \mathbf{E} - \omega \mu \epsilon \sigma \mathbf{E} \Rightarrow -\omega^2 \mu \epsilon \sigma \mathbf{E} \left( n^2 + i \frac{\sigma}{\omega \epsilon} \right) \mathbf{E}$$

$\uparrow$ Damping $\uparrow$

$$= n_e^2 \left( n_R + i n_l \right)^2$$

The plane wave solution

$$\mathbf{E} = \mathbf{E}_0 e^{i \mathbf{k} \cdot \mathbf{r} - i \omega t} \Rightarrow \mathbf{E}_0 e^{-\frac{\mu \epsilon n_y + \mu \sigma n_y}{c} - i \omega t}$$

$\uparrow$

$$\mathbf{k} = \omega \sqrt{\mu \epsilon} \mathbf{n}_c \mathbf{\hat{y}}$$

The irradiance

$$I(y) = I(0) e^{-\alpha y}, \quad \alpha = \frac{\omega}{c} n_l = 2 \sqrt{\pi f \mu \sigma} : \text{attenuation coefficient}$$

For $y = \frac{1}{\alpha}$ the irradiance drops by a factor of $e^{-1}$: skin depth, $\delta$

Example Skin depth of Copper
For UV ($\lambda_o \approx 100$nm) $\delta = 0.6$nm
For IR ($\lambda_o \approx 10,000$nm) $\delta = 6$nm

Little penetration $\rightarrow$ High reflection of light

Metals reflect almost all the incident light (85%~95%) regardless of wavelengths $\rightarrow$ Colorless (Silvery gray)
The Dispersion Equation

Vibration of a bound electron due to the electric field

\[ x(t) = \frac{q/m}{\omega_0^2 - \omega^2 - i\gamma\omega} E(t) \quad : \quad q > 0 \text{, } x \text{ measures from - to +} \]

No restoring force in metals: \( \omega_o = 0 \)

\[ x(t) \text{ is always } 180^\circ \text{ out of phase with } E(t) \]

\[ \text{The reradiated wave cancels the incoming wave} \]

- The Dispersion Relation

Neglect bound charges and neglect \( \gamma \) assuming high frequency

\[ n^2(\omega) \approx 1 - \frac{Nq^2}{\varepsilon_o n_0} = 1 - \left( \frac{\omega_p}{\omega} \right)^2 \quad : \quad \omega_p = \text{plasma frequency} \]

For \( \omega < \omega_p \), \( n \) becomes complex. Exponential decay of the wave

for \( \omega > \omega_p \), \( n \) becomes real. Small absorption. The conductor becomes transparent

Ionosphere: Distribution of free electrons

\( n < 1 \) and real for \( \omega > \omega_p \)

Reflection from a metal

At normal incidence on a metal

\[ R = \left( \frac{n_c - 1}{n_c + 1} \right) \left( \frac{n_c - 1}{n_c + 1} \right)^* \Rightarrow \left( \frac{n_R - 1}{n_R + 1} \right)^2 + n_I^2 \left( \frac{n_R + 1}{n_R - 1} \right)^2 \quad : \quad n_c = n_R + i n_I \]

If \( n_I = 0 \) \quad \rightarrow \quad \text{Dielectric material}

If \( n_I > 0 \) \quad \rightarrow \quad R \text{ becomes larger}

If \( n_I >> n_R \rightarrow \quad n_c \text{ purely imaginary, } R = 1 \)

Reflectance from an absorbing medium

\( n_I \) and \( R \) depend on \( \omega \)

Visor of space suit

Thin gold coating \quad \rightarrow \quad 70\% \text{ reflection}

(Reduction of IR transmission still transmitting VIS)
4.9 The Interaction of Light and Matter

Reflection of all visible frequency $\rightarrow$ White color
70%~80% reflection $\rightarrow$ Shiny gray of metal

Thomas Young: Colors can be generated by mixing three beams of light well separated in frequency

Three primary colors combine to produce white light: No unique set

The common primary colors: $R, G, B$

- Two complementary colors combine to produce white color
  
  $M + G = W,$
  $C + R = W,$
  $Y + B = W$

- A saturated color contains no white light (deep and intense)
  An example of an unsaturated color
  
  $M + Y = (R + B) + (R + G) = W + R$ : Pink

- The characteristic color comes from selective absorption

Example:
1. Yellow stained glass
   White light $\rightarrow$ Resonance in blue $\rightarrow$ Yellow is seen at the opposite side
   $\uparrow$ $\uparrow$ Red + Green
   Strong absorption in blue

2. $H_2O$ has resonance in IR and red
   $\rightarrow$ No red at ~30m underwater

3. Blue ink looks blue in either reflection or transmission
   Dried blue ink on a glass slide looks red.
   $\rightarrow$ Very strong absorption of red.
   Strong absorber is a strong reflector due to large $n_1$.

Resonance of materials
Most atoms and molecules $\rightarrow$ Resonances in UV and IR
Pigment molecules. $\rightarrow$ Resonances in VIS
Organic dye molecules $\rightarrow$ Resonance in VIS

- Subtractive coloration
  Blue light $\rightarrow$ Yellow filter $\rightarrow$ Black at the other side
  $\uparrow$
  It removes blue