So far we've seen reflection, refraction, and scattering. The key points are:

**Reflection**: \( \theta_{\text{in}} = \theta_{\text{out}} \) measured from normal direction

**Refraction**: \( n_1 \sin \theta_1 = n_2 \sin \theta_2 \)

where \( n_1 = \frac{c}{v_1} \)

**Scattering**: Light is absorbed and re-emitted. (Saw that "blue-sky" is because higher frequency blue light is more likely to be scattered).

Today I want to talk in more detail about polarization.
Randomly combined light such as from the sun or a light bulb is the sum (combination) of many different EM waves
- travelling in different directions
  (we only see $I = \frac{\text{Power}}{\text{area}}$)
- different frequencies
  (we perceive that as color, with white being all colors)
- different $\vec{E}$ directions.

A light wave coming at you, say along the x-axis, could be

or, in fact any other rotation. $\vec{E} \perp \vec{B}$ but $\vec{E}$ can point in any direction $\perp x$ is anywhere in the x-z plane.

The direction of the $\vec{E}$ vector is called the polarization direction.

(Note, this is completely unrelated to the "polarization" of dielectrics -- just coincidentally the same name).
Normally, the mish-mash sum of all combined light has $\vec{E}$ pointing randomly. So, if we took monochromatic light in one direction and viewed along its direction of propagation, the different waves have $\vec{E}$ pointing in different directions. (They don’t necessarily cancel to zero since they may have different phase).

Such randomly pointing $\vec{E}$ combinations are called un-polarized waves since there is no simple direction (polarization) for $\vec{E}$.

Suppose we let this wave pass through a set of horizontal conductors.

Waves with horizontal $\vec{E}$ will cause moving charge in the wires. The moved charge produces an opposite $\vec{E}$ field, and $I^2R$ absorbs the energy of the wave.

$\Rightarrow$ Horizontal $\vec{E}$’s blocked.
Then the waves look like this:

```
\[ z \leftarrow \]
\[ \uparrow \]
\[ y \]
```

All the horizontal components have been absorbed and the wave is polarized along the \( \hat{y} \) axis—meaning \( \vec{E} \) only has components along \( \hat{y} \), none along \( \hat{z} \).

Check: (Which way does \( \vec{B} \) point then? Along \( \hat{z} \), \( \perp \) to \( \vec{E} \).)

You might wonder why the contributions between the \( y \) and \( z \) axes got absorbed as well as those that were solely along \( \hat{z} \). That is because any \( \vec{E} \) in the \( y-z \) plane can be separated into a component along \( \hat{y} \) and one along \( \hat{z} \). All the \( \hat{z} \) components were absorbed leaving only the \( \hat{y} \) ones.

Note that this really only makes sense as an analogy if the wires are very thin in the \( \hat{y} \) direction so charge can’t move that way to absorb the \( y \) component of \( \vec{E} \).
For radio waves, with a long wavelength, this works with wires.

For light we need "conductors" that are very thin. Can do that with long molecules--polymers aligned in one direction--embedded in glass or plastic. They absorb light with $\mathbf{E}$ along their direction. More correctly, they absorb the components of the light with $\mathbf{E}$ along their direction.

First use one polarizer to block half of the light. Randomly polarized light has, on average, half as much with $\mathbf{E}$ in one direction as the other.

Note that it actually blocks a little more than half because some gets absorbed by the plastic itself.

Second use a second polarizer. If it is oriented in the same way as the first, it blocks a little of the light--absorbed by the plastic...
If it is oriented perpendicular to the first, it blocks all of the light. I.e. one blocks the $\hat{y}$ component and the other blocks the $\hat{z}$ component. (It doesn't matter what the actual directions are, just that they are mutually perpendicular).

So, what happens if the second polarizer is oriented at an angle somewhere between parallel and perpendicular?

The first makes $\vec{E}$ point only along one axis, horizontal in this case.

The second allows through only the component along its axis. $\Rightarrow E \cos \Phi$. If $\Phi = 90^\circ \Rightarrow 0$.

What we see is the light's intensity,

$$I = \frac{\text{Power}}{\text{area}} = \left| \frac{\mathcal{S}}{\text{avg}} \right| = \frac{1}{2} EB \mu_0 = \frac{1}{2} \frac{E^2}{\mu_0 c}$$

$\Rightarrow E \rightarrow E \cos \Phi \Rightarrow I \rightarrow I \cos^2 \Phi$
Note that this really is only true for an ideal polarizer that absorbs no light when parallel, \( \varphi = 0 \).

What I discussed here is linearly polarized light. The text discusses a different configuration, circularly polarized, which is more complicated. It should now be easy to read -- but not worth our time here.

**Polarization by Reflection**

It turns out that reflected light is polarized, for some angles of reflection. If light is incident on a surface, say glass, some of the light reflects and some refracts. The angles are specified as usual:

\[
\sin \theta_2 = \frac{n_1}{n_2} \sin \theta_1
\]
Now, let's consider the polarization.

$\vec{E}$ has components in both directions perpendicular to the propagation:

- and out of page.

The component parallel to the surface (i.e., out of the page) is reflected more than the component that is not \(\parallel\) to surface.

At a specific angle, \(\Theta_p\), the reflected light has only an \(E\) parallel to the reflecting surface, the other component is refracted but not reflected. That occurs when the reflected and refracted rays are 90° apart, i.e., when the non-parallel \(E\) component of the refracted wave points along the reflected ray.

\[
\sin \Theta_2 = \frac{n_1}{n_2} \sin \Theta_p
\]

\[
\Rightarrow \Theta_2 + \Theta_p = 90° \quad \Rightarrow \Theta_2 = 90° - \Theta_p
\]

\[
\sin \Theta_2 = \sin (90° - \Theta_p) = \cos \Theta_p
\]

\[
\Rightarrow \tan \Theta_p = \frac{n_2}{n_1}
\]

**Brewster's Law**
This is why polarized sunglasses block glare. Glare is reflected light with mostly polarized horizontally.

⇒ "Vertically oriented" polarizing filters in sunglasses will block glare.

Ocean glare is a good example.

What if you are lying on your side?

Note: we already talked about polarization of the blue scattered light in the sky. Try this with your sunglasses.
Demo 84.45: Adding reactants to the water forms a precipitate that scatters light. Transmitted light becomes redder and scattered light (side) blue and polarized.
Another reflection effect that is more readily obvious is that different objects have different color. i.e. containing all polarizations

Unpolarized light shining on a glass surface reflects only the light with one polarization.

In containing all colors

White light shining on an object reflects only certain colors. Actually it absorbs certain colors and reflects the rest.

Red objects absorb yellows and blues.

Blue objects absorb reds and yellows.

The red sky at sunset is an example where the blues are absorbed (and reradiated) leaving red.

Chlorophyll absorbs reds & blues, so the remainder (green) reflects.
Conceptual question: There is a lot of dust in the interplanetary space of the solar system, but very little of it is smaller than \( \approx \frac{1}{3} \) mm across. Why? Radiation pressure from the sun \( \propto r^2 \)
while mass \( \propto r^3 \).

Conceptual question: How could you block microwaves, \( \lambda < 1 \text{cm} \)?
Two grids with spaces \( \leq 1 \text{mm} \).

Conceptual question: How could you "curve" light?
Make \( n \) a function of position e.g. with a solution that has a continuously varying \( n \).

Conceptual question: How could you measure \( n \) for some substance?
Refraction: \( n_1 \sin \theta_1 = n_2 \sin \theta_2 \)
Total internal reflection: \( n_1 \sin \theta_c = n_2 \sin 90^\circ \).

Conceptual question: In what direction is the sun at high noon? Actually it is \( \frac{8 \text{ minutes}}{24 \times 60} \times 360^\circ = 2^\circ \) farther along in the sky because it took 8 minutes for the sunlight to reach us.
Conceputal question:
Which of these rays might be internally reflected?

\[
\begin{array}{c}
\text{Air} \\
1.3 \\
1.5 \\
1.4 \\
1.3 \\
\text{Air}
\end{array}
\]

\[\text{Yes: } \sin \theta_c = \frac{n_2}{n_1} = \frac{1.0}{1.3} \quad \Rightarrow \quad n_1 < n_2\]

\[\text{No: } \sin \theta_c = \frac{n_2}{n_1} = \frac{1.0}{1.5} \quad \Rightarrow \quad n_1 > n_2\]

For total internal reflection.

Sample problem: What is the index of refraction of this liquid if the observer can see the opposite bottom corner?

\[
\sin \theta_c = \frac{n_2}{n_1} = \frac{1.0}{n_1}
\]

\[n_1 = \frac{1.0}{\sin \theta_c}\]

\[= \frac{1.0}{\sqrt{110/\sqrt{85^2 + 110^2}}}\]

\[= \frac{\sqrt{85^2 + 110^2}}{110} = \frac{139}{110} = 1.26 \quad \text{less than water.}\]