Lecture #21

Optics and Mirrors
Wave comes in with a frequency $f$.
Wave length is $\lambda = c/f$

Is wave length of reflected wave equal to wave length of incident wave?

(a) Yes  (b) No

Figure 34-8  Physics for Engineers and Scientists 3/e
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Basic law of optics
angle of incidence = angle of reflection

Angles of incidence ($\theta$) and reflection ($\theta'$) are measured with respect to perpendicular.

Figure 34-9 Physics for Engineers and Scientists 3/e
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Incident ray strikes first mirror with angle of incidence $\theta$.

Two flat mirrors are at right angles. What is angle of reflection at second mirror?

(a) $\theta$
(b) $45^\circ$
(c) $90^\circ - \theta$

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Image may not be where you think it appears to be.

Virtual image arises from law of reflection.

All light rays arriving at your eye seem to come from a point behind the mirror, the image point.

Since light does not really emerge from image point, image is virtual.
Mirror images from plane surfaces.

Image is erect, but image is reversed.

Mirror images of letters are reversed.
Front-to-back reversal: mirror image of a hand facing north is a hand facing south.

The mirror image of a left hand is a right hand, and vice versa.
velocity of light changes in different materials
index of refraction \( n = \frac{c}{V_m} \) (velocity of light in vacuum/velocity of light in material)

frequency of light signal
the same in vacuum and material

wavelength changes
from vacuum to material
\( \lambda_m = \frac{\lambda_{\text{vac}}}{n} \)

\( \lambda_{\text{air}} = 0.5 \times 10^{-6} \) m

Slower wave speed in water causes wave fronts to bunch up; wavelength of light in matter is shorter than in air.

Figure 34-15 Physics for Engineers and Scientists 3/e
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<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air, 1 atm, 0°C</td>
<td>1.000 29</td>
</tr>
<tr>
<td>1 atm, 15°C</td>
<td>1.000 28</td>
</tr>
<tr>
<td>1 atm, 30°C</td>
<td>1.000 26</td>
</tr>
<tr>
<td>Water</td>
<td>1.33</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>1.36</td>
</tr>
<tr>
<td>Castor oil</td>
<td>1.48</td>
</tr>
<tr>
<td>Quartz, fused</td>
<td>1.46</td>
</tr>
<tr>
<td>Glass, crown</td>
<td>1.52</td>
</tr>
<tr>
<td>light flint</td>
<td>1.58</td>
</tr>
<tr>
<td>heavy flint</td>
<td>1.66</td>
</tr>
</tbody>
</table>

*a*For light of wavelength $\approx 550$ nm.
Law of Refraction (Snell's Law)

\[ \frac{\theta_i}{\theta_r} = \frac{n_2}{n_1} \]

\[ n_1 \sin \theta_i = n_2 \sin \theta_r \]

\[ \sin \theta_r = \frac{n_1}{n_2} \sin \theta_i \]

If \( n_2 > n_1 \), wave is refracted towards normal.

Also note: Incident intensity can be partially reflected, and partially transmitted. Is there any other possibility?
Law of Refraction holds if $n_2 > n_1$

Waves refracted away from normal

$n_2 \sin \theta_i = n_1 \sin \theta_e$

$n_2 > n_1$

Critical ray is refracted along surface.

$n_2 \sin \theta_{cr} = n_1$

$\sin \theta_{cr} = \frac{n_1}{n_2}$

$n_2 > n_1$

$\theta_i > \theta_{cr}$

For angles larger than $\theta_{crit}$, refraction is impossible. Total internal reflection occurs.

Figure 34-21 Physics for Engineers and Scientists 3/e © 2007 W. W. Norton & Company, Inc.
hidden fish

water
Light Pipe (Optical Communication)
(or optical fiber)

PIP 34 figure 1  Physics for Engineers and Scientists 3/e
Hank Morgan/Photo Researchers, Inc.
Refraction also leads to virtual image

Image of fish is at intersection of extrapolated refracted rays.

Where do you aim to spear a fish?

Fish acts as source of light rays.

Figure 34-19 Physics for Engineers and Scientists 3/e
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Generally reflected wave is partially and even totally polarized.

Reflected light is polarized parallel to surface...

\[ \phi = 90° - \theta_p \]

...when reflected and refracted rays are perpendicular.

This geometry leads to

\[ \tan \theta_p = n \]

Is the transmitted wave partially polarized?

(a) yes  (b) no
Velocity of light depends on frequency \( \left( \frac{c}{v_w} \equiv n \right) \)

In ordinary materials, the index of refraction \( n \) increases slightly at shorter wavelengths.
Consequence: long wavelength refracted less than short wavelength.

In ordinary materials, long wavelengths (red) are refracted less than short wavelengths (violet).

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Refraction can lead to splitting of colors of white light, or identifying frequencies of molecules (a "light print").

(a) Colored light emitted by atoms in a discharge tube...

...has a discrete spectrum of just a few colors.

(b) Ultraviolet: 410 nm; violet: 434 nm; blue-violet: 486 nm; blue-green: 537 nm; red: 656 nm.
For any incident ray parallel to axis, reflected ray crosses focal point, at $F = R/2$.

$F = R/2$

For a concave mirror, $F > 0$ is convention.
Convex mirror leads to a virtual focal point

For incident rays parallel to axis, reflected rays diverge.

For convex mirror

\[ F < 0 \]

Extrapolated divergent rays appear to come from a focal point behind mirror.

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Image of Point P (the source)

All Rays from P focus on P' (the image)

These and all rays from P converge at P', the image point.
\( S = \text{distance of source to mirror} \)

$$f = \frac{B}{2}$$

**Basic relations**

\[
\frac{1}{S} + \frac{1}{S'} = \frac{1}{f}
\]

**Magnification:**

\[
M = \frac{h'}{h} = -\frac{S'}{S}
\]

Real image is inverted

\( s' = \text{distance of image to mirror} \)
For object near convex mirror...

\[ \frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \quad \text{if} \quad f < 0 \quad \text{for convex mirror} \]

\[ M = \frac{h'}{h} = -\frac{s'}{s} \]

\[ 0 < M < 1 \]

...image is at intersection of extrapolated reflected rays.

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Conventions for mirrors

\[ \frac{1}{S} + \frac{1}{S'} = \frac{1}{f} \]

- $S > 0$ = source distance to left of mirror
- $S' > 0$ = real image distance to left of mirror
- $S' < 0$ = virtual image distance to right of mirror
- $f > 0$ = focal distance of concave mirror
- $f < 0$ = focal distance of convex mirror
Convex mirror only produces reduced (|M|<1), upright (M>0) image, and virtual (s'<0) image.

Image behind mirror is virtual; light only appears to come from image.
concave mirrors can produce

(a) virtual, upright and magnified \((|M|>1)\) image if \(0 < s < f\)

(b) real, inverted \((M<0)\), and magnified \((|M|>1)\) if \(f < s < 2f\)

(c) real, inverted and reduced \((|M|<1)\) if \(2f < s < \infty\)

(example: optical mirror telescope)

Image is real; light rays actually cross and diverge from image point.

Figure 34-41a  Physics for Engineers and Scientists 3/e
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