Light Through a Medium

Unit 5: The Wave Nature of Light

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Grade 12 Physics
Olympiads School

Summer 2019

Files for You to Download

The “print version” the class slides for this unit are now downloadable from the school website:

- `Phys12-4a-lightMedium-print.pdf` in space
- `Phys12-4b-lightInterference-print.pdf`
- `Phys12-4c-emWave.pdf`

As usual, if you wish to print out the slides, we recommend printing 4 slides per page. Please download/print the PDF file before the start of each unit. There is no point copying notes that are already printed out for you. Instead, take notes on things that are not necessarily on the slides.

Where Are We In the Course

1. Fundamentals of Dynamics
2. Momentum, Impulse and Energy
3. Gravitational, Electric and Magnetic Fields
4. Wave Nature of Light
5. Theory of Special Relativity
6. Introduction to Quantum Mechanics

So What is Light Anyway?

Is light a wave or a particle?

- If it's a particle, it should behave like particles (e.g. billiard balls) and we can apply our equation of motion to describe its behaviour
- If it's a wave it should behave like all other waves (e.g. ocean waves) and we can apply our wave equations to describe its behaviour
- **In this unit, I'll argue that light is a *wave*, and I'll show you how to work with light by treating it as a wave.**

In This Unit

In this unit, we will be discussing some important properties of light:

- Light waves passing through a medium
    - Reflection
    - Refraction
    - Dispersion
- Light waves passing through an opening
    - Diffraction
    - Interference
    - Optical resolution
- What kind of wave is light?
    - Maxwell's equations
    - Electromagnetic waves
    - Polarization of light
    - Speed of light

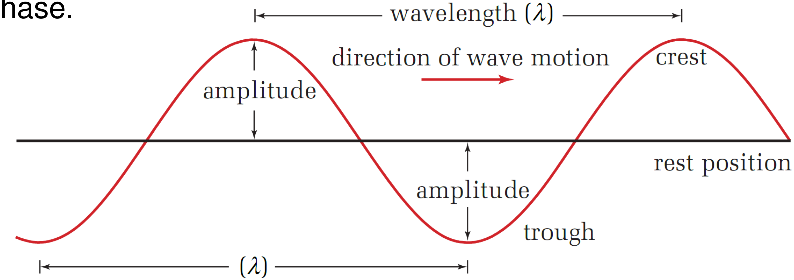
What is a Wave?

A mechanical wave. . .

- Transports energy through a medium
    - Does not transport matter
- The particles in the medium are excited by vibrations in neighbouring particles
    - The medium has a net displacement of zero
    - The vibration get transferred to the next particle

Describing a Wave

- **Crest**: highest point
- **Trough**: lowest point
- **Wavelength**: shortest distance between two points in the medium that are in phase.



(The easiest way to measure wavelength is from crest to crest, or from trough to trough.)

Universal Wave Equation

The speed of a wave is related to its wavelength and the frequency by the **universal wave equation**:

$$\boxed{v = f\lambda}$$

Quantity	Symbol	SI Unit
Wave speed	v	m/s
Frequency	f	Hz
Wavelength	λ	m

Universal Wave Equation

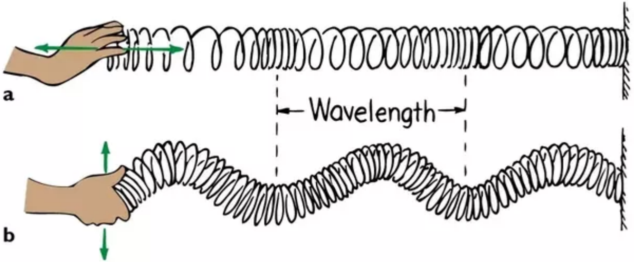
Frequency of a wave (f)

- Number of complete wavelengths that pass a point in a given time interval
- Same as the frequency of the disturbance that generated the wave
- **Depends only on the source that is producing the wave**

Speed of a wave (v)

- The speed at which the wave fronts are moving
- **Depends only on the medium**

Two Kinds of Waves



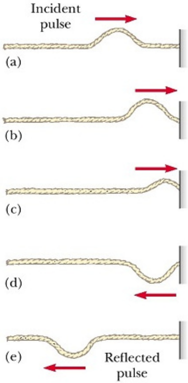
a. **Longitudinal wave**
   - Particles of a medium vibrate parallel to the direction of the motion of the wave
   - Example: sound waves

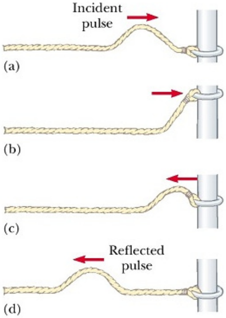
b. **Transverse wave**
   - Particles of a medium vibrate at right angles to the direction of the motion.
   - Example: ocean waves, electromagnetic waves

Reflection of Wave at a Boundary

When a wave on a string reflects at a boundary, how the reflected wave looks depends on the type of boundary

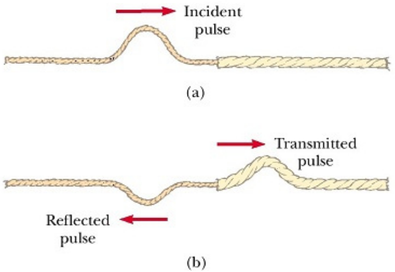
- At a *fixed end* (left), the reflected wave is *inverted* (180° phase shifted; a crest becomes a trough)
- At a *free end* (right), the reflected wave is upright





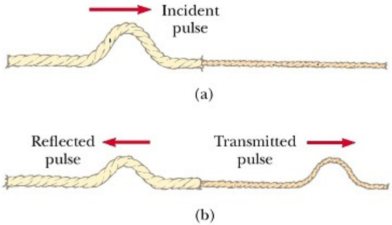
Transmission of Waves: Fast to Slow Medium

- Reflected wave:
  - Inverted (180° phase shifted)
  - Same frequency and wavelength as the incoming wave
  - The amplitude is decreased
- Transmitted wave:
  - Upright
  - Same frequency as incoming wave, but has a shorter wavelength because the wave slowed down

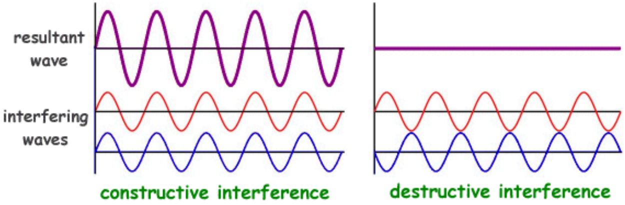


Transmission of Waves: Slow to Fast Medium

- Reflected wave:
  - Upright
  - Same frequency and wavelength as the incoming wave
  - The amplitude is decreased
- Transmitted wave:
  - Upright
  - Same frequency as incoming wave, but has a longer wavelength because the wave sped up



Superposition of Waves



- **Principle of Superposition:** When multiple waves pass through the same point, the resultant wave is the *sum* of the waves
- The consequence of the principle of superposition is *interference of waves*. There are two kinds of interference:
  - **Constructive interference:** Two wave fronts (crests) passing through creates a wave front with greater amplitude
  - **Destructive interference:** A crest and trough will cancel each other

Huygens' Principle

In the 1600's there were two competing theories of light...

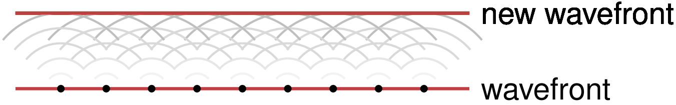
- Some scientist (including Issac Newton) believed that light is a particle
- Others, including Christiaan Huygen (Dutch) and Augustin-Jean Fresnel (French), believed that light is a wave

Huygen's princple: all waves are in fact an infinite series of circular wavelets

Applying Huygen’s Principle

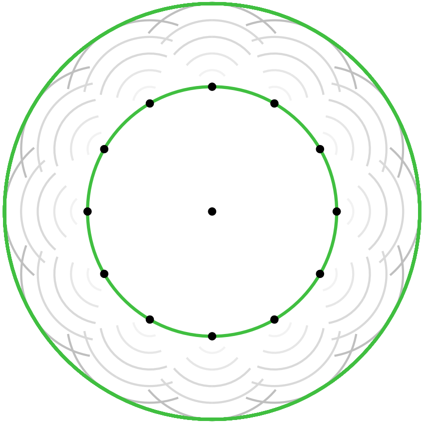
Planar Wave

- To predict the propagation of the wavefront, we treat the current wavefront as a series (infinite series) of circular wavelets
- Each wavelet propagates radially outward at the same wave speed
- The wavelets then tell us where the wavefront will be moved to after a finite time interval



Applying Huygen's Principle

Cicular Wave



- To predict the propagation of the wavefront, we treat the current wavefront as a series (infinite series) of circular wavelets
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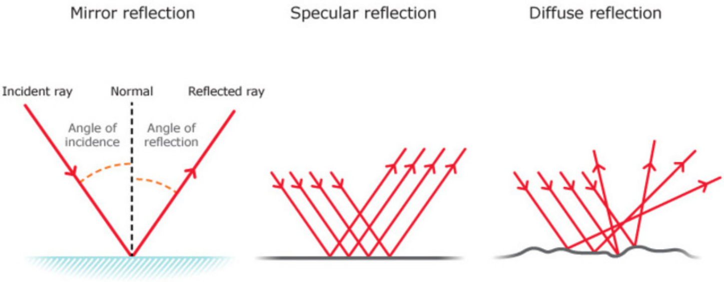
Reflection of Light

Law of Reflection

The incident ray, the reflected ray, and the normal to the surface of the mirror all lie in the same plane, and the angle of reflection is equal to the angle of incidence.



Specular Reflection

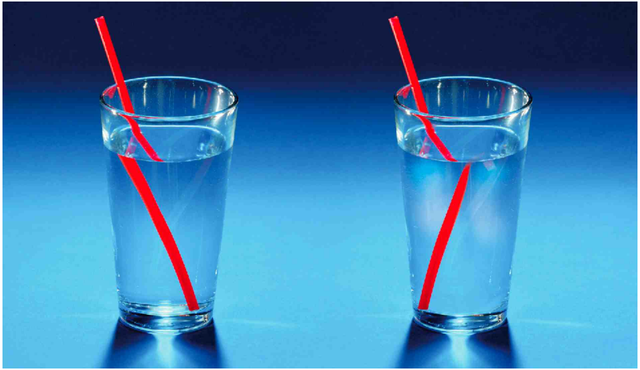
Example: Lake Reflection

This photo of Lake Matheson shows specular reflection in the water of the lake with reflected images of Aoraki/Mt Cook (left) and Mt Tasman (right). The very still lake water provides a perfectly smooth surface for this to occur.

Refraction of Light Through a Medium

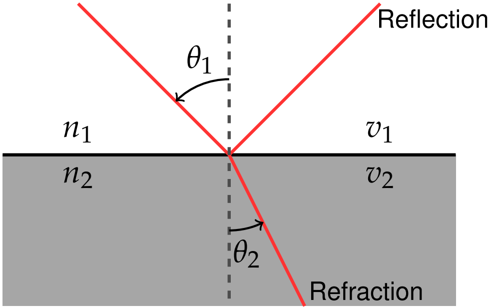
Refraction is the change in wave speed when the wave enters another medium.

- When the wave enters the medium an angle, the change of wave speed causes the wave to change direction (e.g. from air to water, air to glass, glass to air etc)
- The amount of bending depends on the **indices of refraction** of the two media



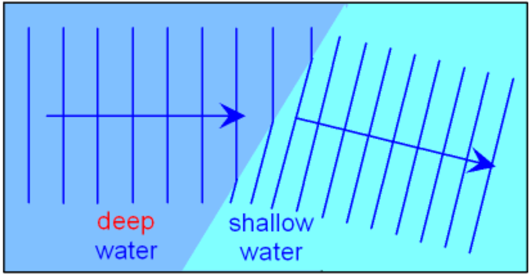
Refraction of Light Through a Medium

You have probably all seen this diagram. When light enters from one medium to another, it both reflects and refracts



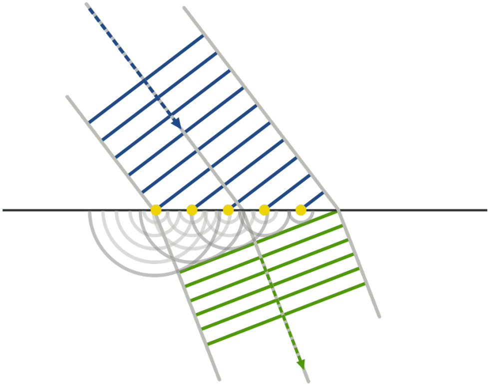
The reflection follows the law of reflection; the angle θ_2 is determined by Snell's law.

Refraction Happens in Ocean Waves Too!



Refraction happens not only with light, we see the same behaviour in ocean waves, when the wave travel from deeper water (faster waves) to shallow depths.

Refraction and Huygens Principle



We can explain the refraction phenomenon using Huygens' principle

Snell's Law

Snell's law relates the indices of refraction n of the two media to the directions of propagation in terms of the angles to the normal.

$$\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

Variable	Symbol	SI Unit
Indices of refraction of the media	n_1, n_2	(no units)
Incident angle of light	θ_1	(no units)
Refraction angle of light	θ_2	(no units)

Index of Refraction

Index of refraction (n), or **refractive index**, is defined as the speed of light in vacuum (c) divided by the speed of light in the medium (v):

$$\boxed{n = \frac{c}{v} = \frac{\lambda_{\text{vacuum}}}{\lambda}}$$

When light enters a second medium, the *frequency* remains unchanged (i.e. the colour doesn't change!) but since the speed changes, the *wavelength* also changes:

$$\boxed{\frac{n_1}{n_2} = \frac{\lambda_2}{\lambda_1}}$$

(Work this out using the universal wave equation!)

Index of Refraction of Common Materials

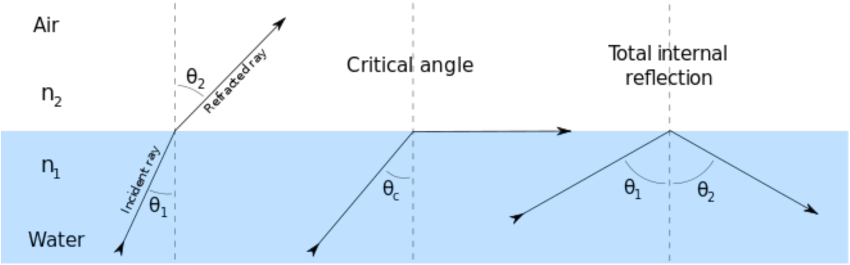
Material	n	**Material**	n
Vacuum	1	Ethanol	1.362
Air	1.000277	Glycerine	1.473
Water at $20\,^{\circ}$C	1.33	Ice	1.31
Carbon disulfide	1.63	Polystyrene	1.59
Methylene iodide	1.74	Crown glass	$1.50 - 1.62$
Diamond	2.417	Flint glass	$1.57 - 1.75$

The values given in this table are *average values*. They do not account for variations with wavelength which causes *dispersion*. More on that later!

Total Internal Reflection

From High Index to Low Index

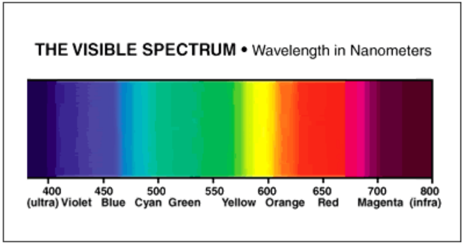
Snell's law still holds, but something weird can happen:



Critical angle θ_c for water-air interface is 48.6°. If incident angle is greater $\theta_1 > \theta_c$, we have **total internal reflection**. TIR can only happen going from a higher index to a lower index, $n_1 > n_2$.

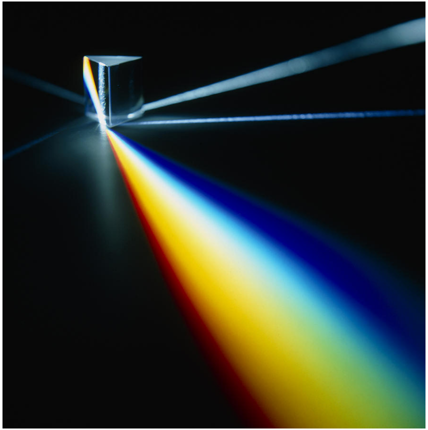
Colour of Light and Wavelength

Human eyes perceive different frequencies of light as different colours. The visible spectrum of light:



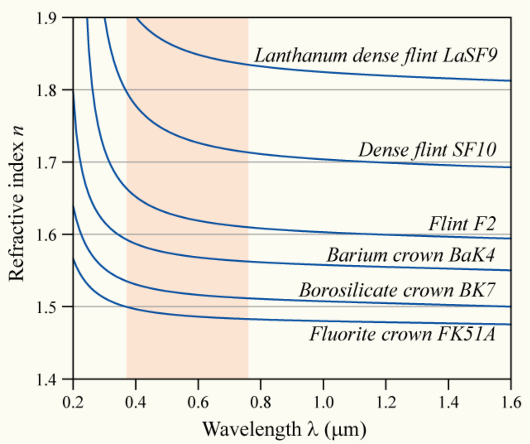
- The “colour” of the light depends on its frequency (& wavelength when it’s in a vacuum)
- *White light* is light that contains waves in all frequencies.

Dispersion of Light Through Refraction



- **White light** is a light that is composed of multiple colours in the visible-light spectrum
- When white light passes through a prism it is separated into different colours
- This is because the refractive index n varies slightly with wavelengths (without this variation, we'd never see a rainbow)
- The phenomomen is of splitting light into its component colours is called **dispersion**

Wavelength Dependency of Index of Refraction



Chromatic Aberration

This is What Disperson Can Do!

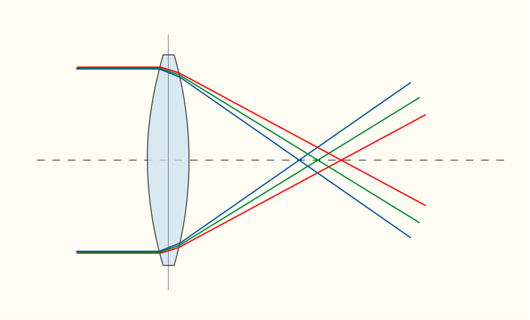
When looking at an image through a cheap binocular, magnifying glass, or telescope, we see the edges of images blurred with a rainbow-coloured edge:

Chromatic aberration can occur even with high-quality camera lenses, particularly with wide-angle lenses where light has to refract from high angles towards the camera sensor/film

Chromatic Aberration

This is What Disperson Can Do!

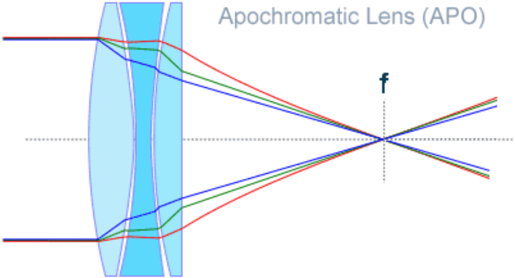
The reason that chromatic aberration happens is the same reason that prisms work: **dispersion of light**



The focal lengths for different frequencies (colour) of light are different, thus blurring the image. So how do we fix it?

Chromatic Aberration: Camera Lens Design

By arranging different lenses of different materials and geometries, we can correct for the chromatic aberration.



Lens design is a closely guarded secret by camera companies. Shape of the lens, material and coating are all factors. A “lens” on a DSLR camera can have up to 30 lens “elements”