Electromagnetism + Optics

Kurzgesagt video (5min)

History (20 min)

5th century BCE: plato thought eyes emitted light rays that return information

others like Epicurus thought objects themselves emitted light

↳ why bad? can't see in dark

1000 yrs later, Alzahen (iraq) thought light was bouncing off objects "father of modern optics"

in 1700's scientists debated — is light a particle or a wave?

Newton: it's a particle with mass (popular)

- light only travels in straight lines, was bend around obstacles
  - explains reflection
  - refraction = light accelerates due to gravity in a medium

others: it's a wave

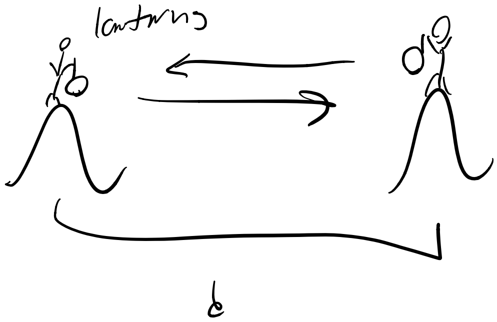
- Hooke: "pulse theory"
- Huygens 1690: Treatise on light
  - ↳ Huygen's principle: sum of spherical wave fronts
  - luminiferous aether

Speed of light:

2400 yr ago, Empedocles wrote that light travels with finite speed.

(Aristotle thought it was infinite)

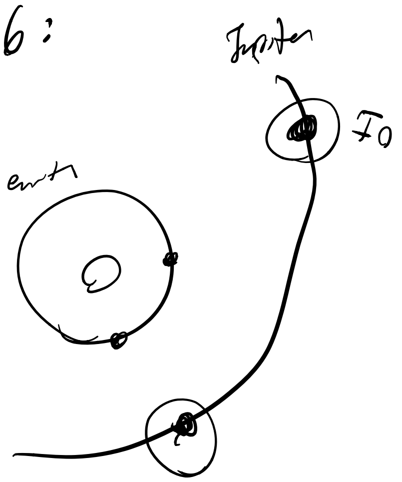
1667: Galileo tries to measure c:



$$\frac{2d}{\Delta t} = c$$

Control for reaction time, $\Delta t \approx 0$

1676:



eclipse time lags

↓

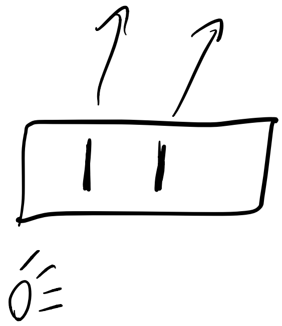
$c \approx 2.14 \times 10^{8}$ m/s

pretty good!

1700s – 1980s: $c \to 2.99E8$ m/s

1983: $c \equiv 299\ 292\ 458$ m/s

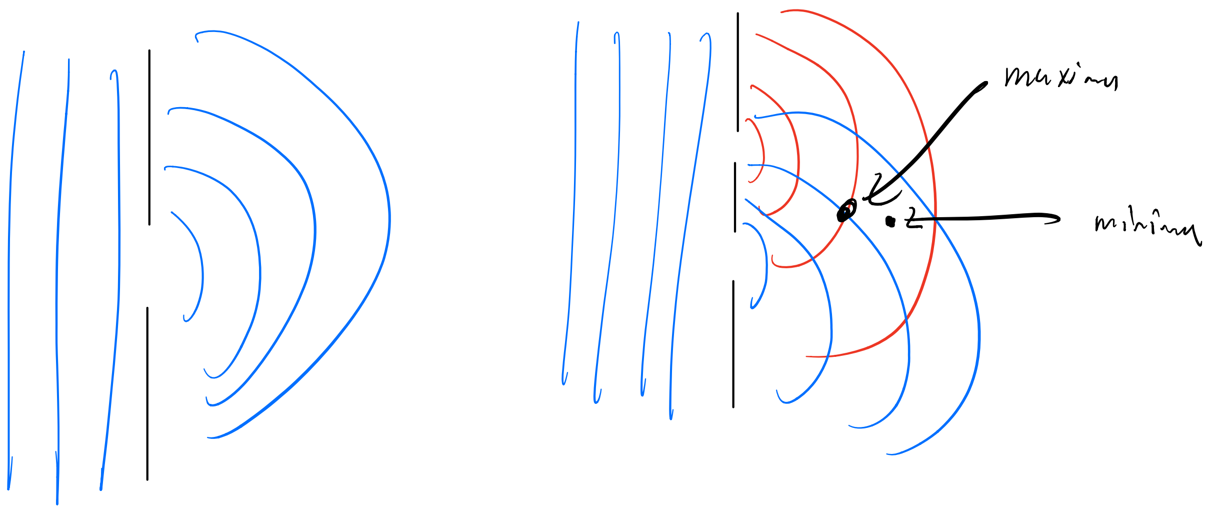
1801: Young's double slit experiment (photons)



particle or wave?

Do double slit experiment

Diffraction:



Slit experiment had fringes,
so light is a wave!

Okay great, we've solved light & we're done, right?

To be continued...

1845: Faraday discovers that polarization of linearly polarized light rotates when $\vec{B} \parallel$ light rays in a dielectric

↳ Faraday rotation

∴ light is related to electromagnetism

↓

Inspired James Clerk Maxwell to study light

1847: Faraday: light is high frequency EM vibrations

1855: Maxwell puts all knowledge of EM into a set of <u>twenty</u> diffeqs with 20 variables

1862: Discovers self-propagating EM waves travel at $v \approx c$

$\rightarrow 3.11\text{e}8$ m/s

1873: Maxwell's "A Treatise on Electricity and Magnetism"

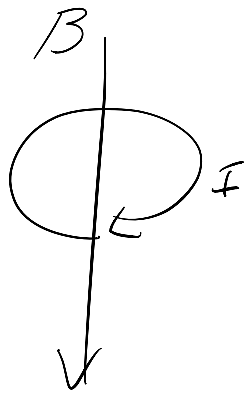
1881: Oliver Heaviside replaces "potential field" with electric + magnetic fields, reducing 20 → 4 → "needed to be murdered"

↳ 4 partial diffeqs: Maxwell's equations

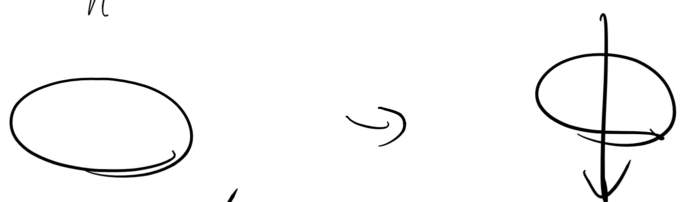
Electromagnetic induction (10 min)

coil produces magnetic field

Current caused by potential difference V



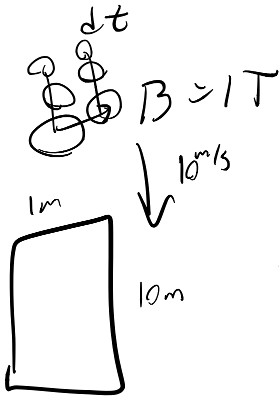
What happens if we turn on field to coil?



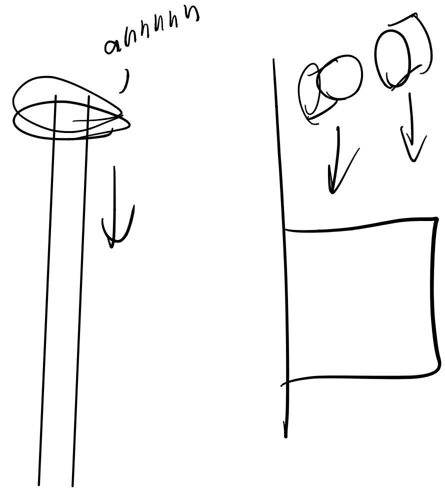
Induction!

magnetic flux: $\Phi_B = \iint_A \vec{B} \cdot d\vec{A}$

induction law: $V = \frac{-d\Phi_B}{dt}$



Ex) inductive braking



What is V?

$V = \frac{d\Phi}{dt} = \cancel{\frac{dB}{dt} A} \cdot \frac{dA}{dt} B$

$= B \cdot \frac{dA}{dt}$

$= B \cdot 1m \cdot 10m/s$

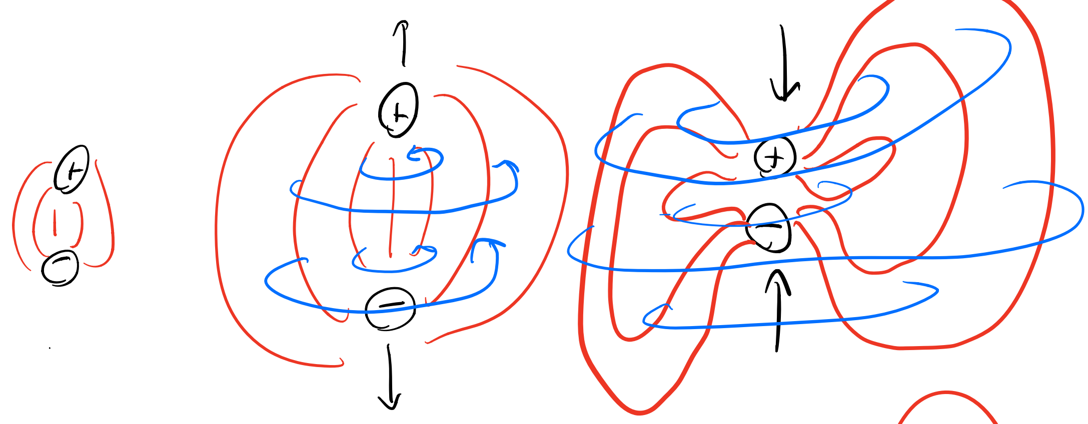
$= 10$ volts!

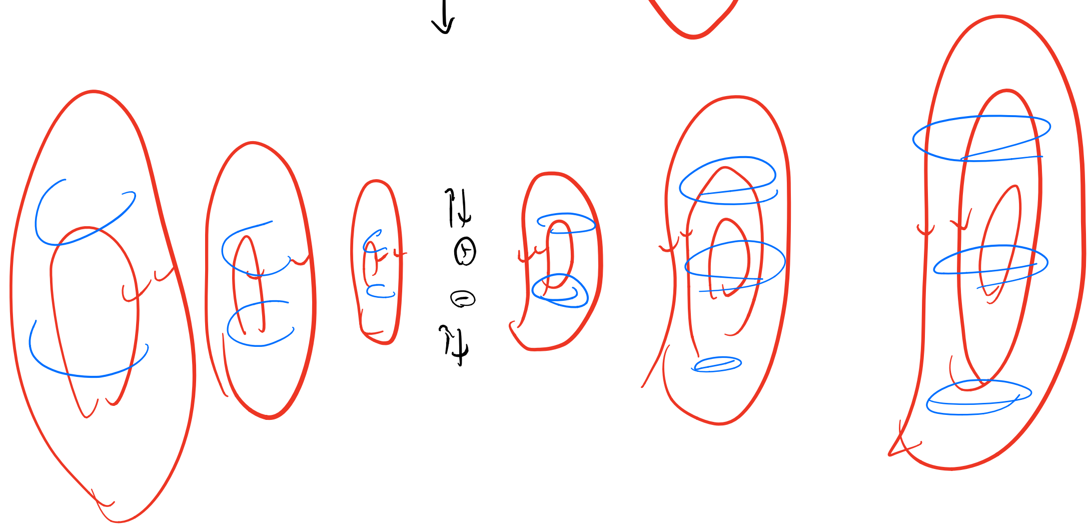
EM waves (10 min)

Charged particle produces $\vec{E}$ field

Moving particle produces $\vec{B}$ field

accelerating charged particle produces EM wave





$$B \to H = \frac{B}{\mu_0} = \frac{\text{Teslas}}{\mu_0} = \frac{\text{amps}}{\text{meter}}$$

$$E \to \frac{V}{m}$$

$$\frac{\text{Tesla}}{\mu_0} \cdot \frac{V}{m} = \frac{W}{m^2}$$

power flux

$$\vec{S} = \vec{E} \times \vec{H}$$

poynting vector

Maxwell's equations

(30 min)

possibly *the* most important equations in all of physics

$Q_{enc} = \iiint_V \rho \, dV$ ← charge density

Integral form:

Gauss's law $\oiint_{\partial V} \vec{E} \cdot d\vec{A} = \frac{Q_{enc}}{\varepsilon_0} = \iiint_V \rho \, dV$

Gauss's law for magnetism $\oiint_{\partial V} \vec{B} \cdot d\vec{A} = 0$ ← no magnetic monopoles!

Ampere's circuital law $\oint_{\partial A} \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$

$= \mu_0 \left(\frac{d}{dt} Q_{enc} + I_{free} \right)$

$= \mu_0 \left(\frac{d}{dt} \varepsilon_0 \iint_A \vec{E} \cdot d\vec{A} + \iint_A \vec{J} \cdot d\vec{A} \right)$

Biot Savart:

$B = \frac{\mu_0}{4\pi} \int_C \frac{I}{|r|^3} \, d\vec{l} \times \vec{r}$

↓

$\vec{B}$ from a wire:

$B = \frac{\mu_0 I}{2\pi r}$

$\oint_C \vec{B} \cdot d\vec{l} = \cancel{2\pi r} \frac{\mu_0 I}{\cancel{2\pi r}} = \mu_0 I$

Faraday's law of induction $\oint_{\partial A} \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \Phi_B = -\frac{d}{dt} \iint_A B \cdot dA$

Differential form:

$$\boxed{\begin{aligned} \nabla \cdot \vec{E} &= \frac{\rho}{\varepsilon_0} \\ \nabla \cdot \vec{B} &= 0 \\ \nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\ \nabla \times \vec{B} &= \mu_0 \left(\varepsilon_0 \frac{\partial \vec{E}}{\partial t} + \vec{J} \right) \end{aligned}}$$

What are μ_0, ε_0?

ε_0 measures amount of charge needed to make one unit of flux

μ_0 measures degree of magnetization in response to a magnetic field

speed of light: $c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$

related to $\alpha = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{\hbar c}$ ...

Break, AMA, set up labs

~75 min before

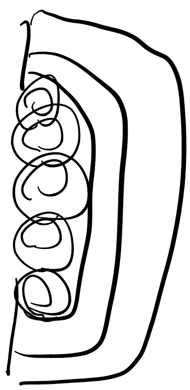
Diffraction (10 min)

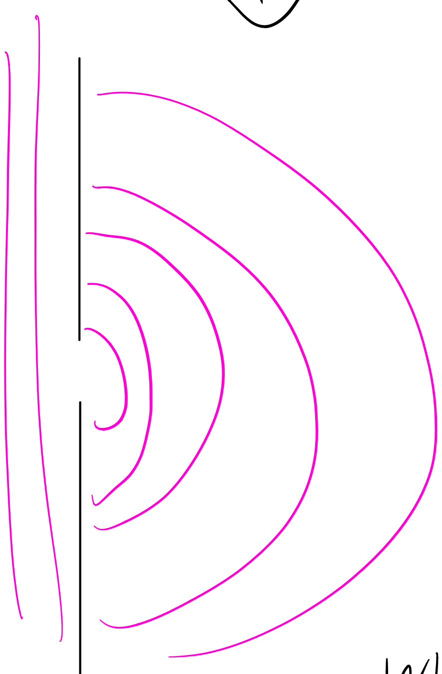
phenomenon when a wave encounters an obstacle or slit

Single slit diffraction

Huygens-Fresnel principle

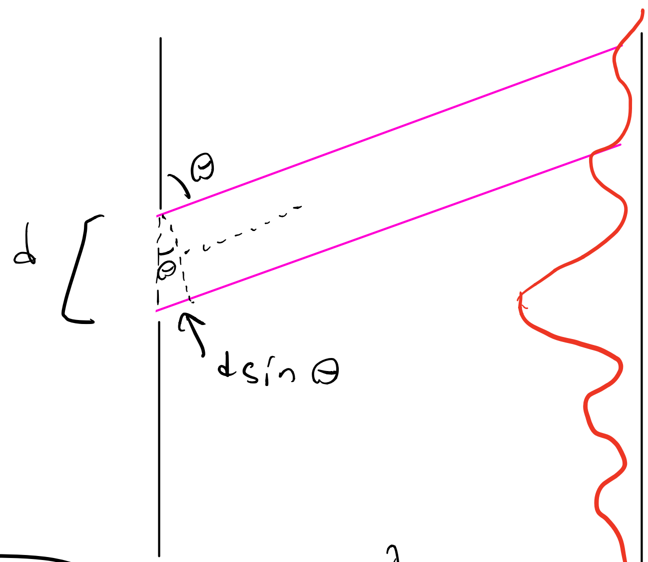
every point on a wavefront is the source of spherical wavelets





$\rightarrow$

Ray picture:



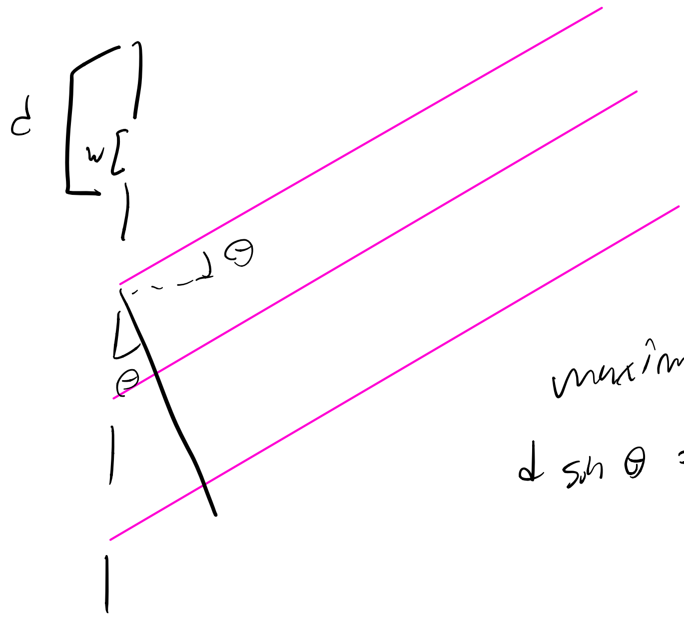
When $d \sin\theta_{min} = \lambda$, $\frac{d}{2}\sin\theta = \frac{\lambda}{2} \rightarrow \pi$ phase shift

so top cancels middle, just below top cancels just below middle, etc. $\rightarrow$ diffraction minimum

Do single slit diffraction demo in laser tank

Diffraction gratings (10 min)

lots of single slit diffractions!



maxima when in phase!

$d \sin\theta = 2d\sin\theta = 3d\sin\theta = \dots = n\lambda$

$d \sin\theta_{max} = n\lambda$

2 lasers:

Green: 530nm

Red: 650nm

2 gratings:

1000 mm^{-1} → $d = 1\mu m$

500 mm^{-1} → $d = 2\mu m$

Find principal $(n=1)$ θ for all 4 combos:

$\theta = \sin^{-1}\left(\frac{\lambda}{d}\right)$

Green/500: $\theta \approx 15.37°$

Green/1000: $\theta \approx 32.01°$

Red/500: $\theta \approx 18.97°$

Red/1000: $\theta = 40.54°$

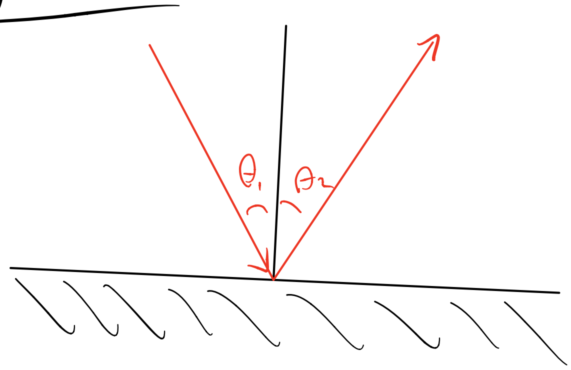
Do laser tank + gratings demo ← ~100 min

Ray optics (5 min)

Simplified model of optics that assumes light is a ray that travels in straight lines

↳ only useful when $x_{min} \gg \lambda$

Reflection



$\Theta_1 = \Theta_2$

Show laser tank w/ shown mirror

Refraction (10 min)

change in direction of a wave passing from one medium to another

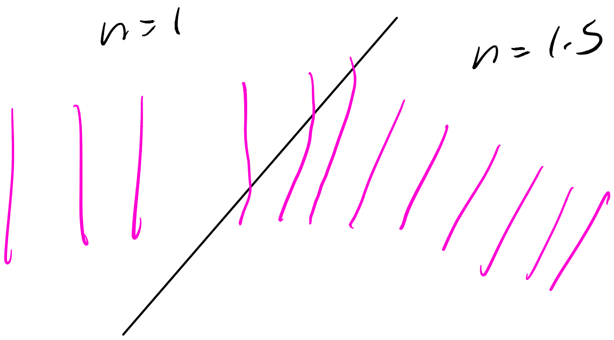
↳ why straws look bent in water

Refractive index

a number describing how fast light propagates in a medium

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

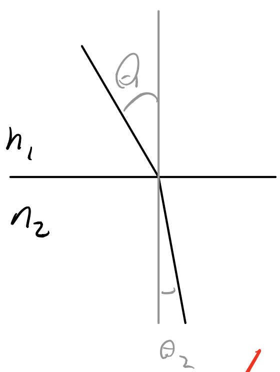
$n = 1$	vacuum	
$n = 1.0002$	air	
$n = 1.3$	water	
$n = 1.5$	glass	
$n = 2.4$	diamond	(sparkly!)



(show wiki image)

Snell's law

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



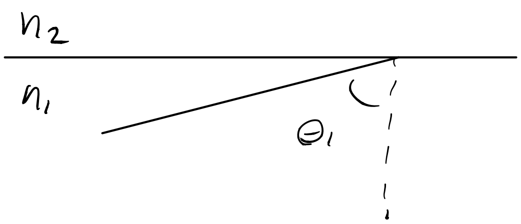
Ex) air to water, $\theta_1 = 15°$

$$\theta = \sin^{-1}\left(\frac{1}{1.3}\sin(15°)\right)$$

$$= 11.48°$$

Total internal reflection (5 min)

What if $n_1 > n_2$ and θ_1 is large?



$$\theta_2 = \sin^{-1}(>1) \quad ?$$

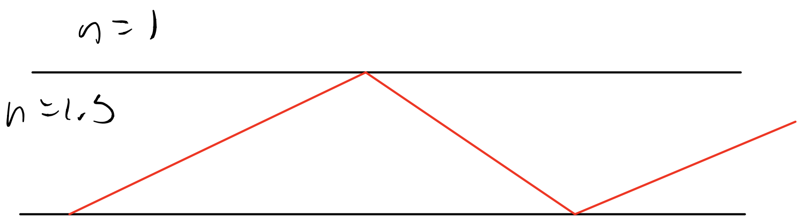
↓

Total internal reflection!
no transmitted light

↗ what makes top of water in pool look like a mirror

(5 min)

Fiber optic cables ← waveguides



↘ no emitted light

Do TIR demo

Chromatic dispersion + prisms (~10 min)

Dispersion: velocity of wave depends on frequency

Index of refraction not same for all frequencies!

Optical constants of GLASS

BK7 optical glass (crown)

Wavelength: 0.5876 ↵ μm (0.3 – 2.5) line select unit converter

Refractive index [i]

$n = 1.5168$

Extinction coefficient [i]

$k = 9.7525\text{e-}9$

Derived optical constants

Relative permittivity (dielectric constants) [i] [i]

$\epsilon_1 = 2.3007$

$\epsilon_2 = 2.9585\text{e-}8$

Absorption coefficient [i] [i]

$\alpha = 0.0020857\ \text{cm}^{-1}$

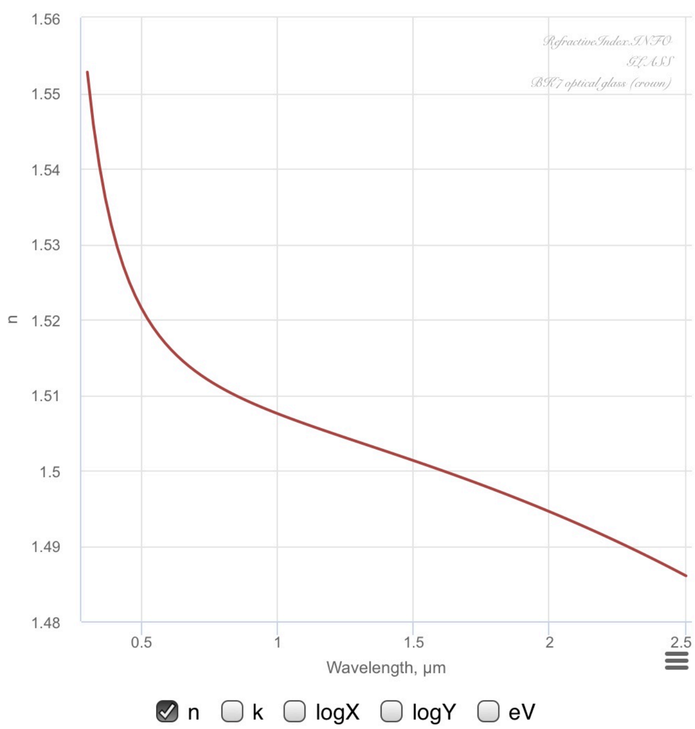
Abbe number [i]

$V_d = 64.17$

Abbe diagram

Chromatic dispersion [i]

$dn/d\lambda = -0.041792\ \mu\text{m}^{-1}$



Violet: $n \approx 1.5295$ (400 nm)

red: $n \approx 1.5131$ (700nm)

ex) What is the angle of a rainbow?

$\theta_1 = 30^\circ$

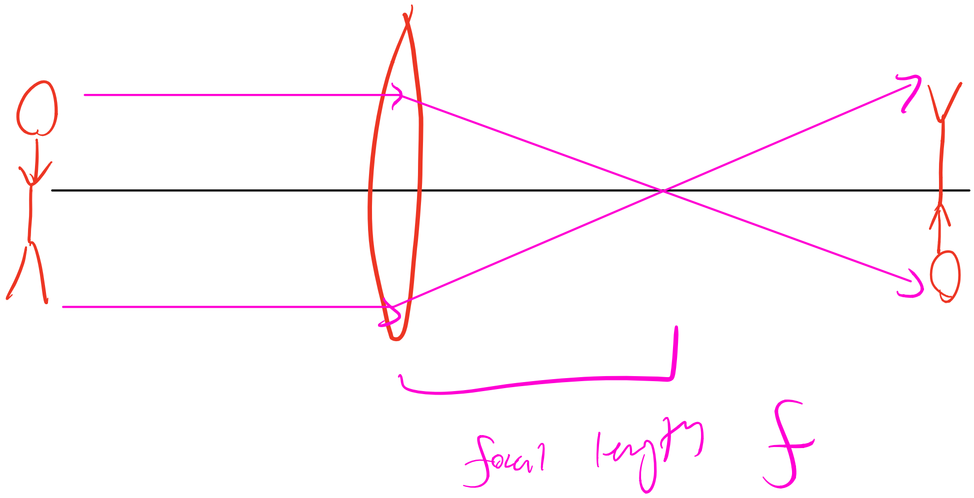
$\theta_{2,red} = \sin^{-1}\left(\frac{1}{1.513}\sin\theta_1\right) = 19.3^\circ$

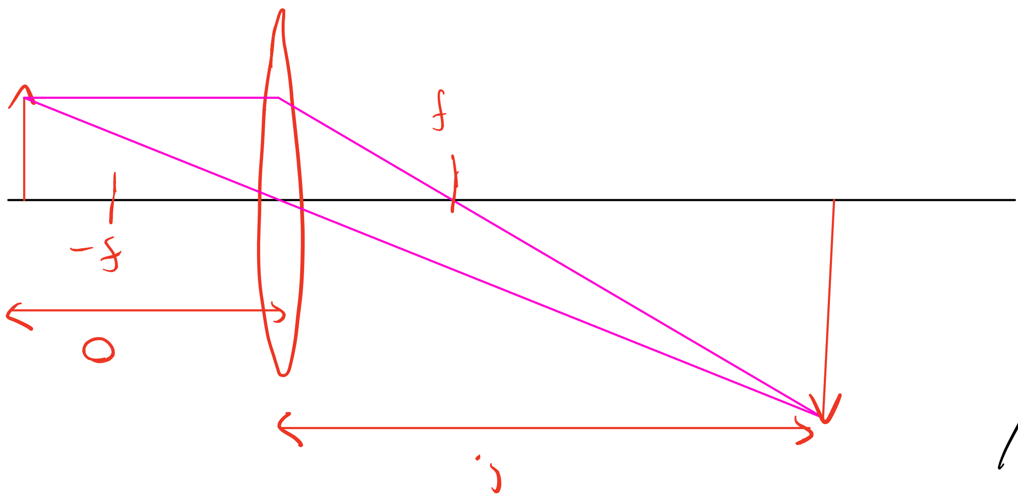
$\theta_{2,violet} = \sin^{-1}\left(\frac{1}{1.5295}\sin\theta_1\right) = 19.08^\circ$

about 0.22°!

~135 min

Lenses, magnifiers, and images (10 min)





Magnification:

$$M = -\frac{i}{o}$$

Thin lens equation: $\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$

ex)

$o = 1m$
$f = .75m$
what is i?

$$i = \frac{-1}{\frac{1}{o} - \frac{1}{f}} = \frac{-1}{1 - \frac{1}{.75}} = 3m$$

$M = -\frac{i}{o} = -3 \rightarrow$ 3x as big, inverted

TODO: Sellmeier's equation?

Time remaining: Lorentz-Drude model

Photoelectric effect

Cs + Zn emit electrons when exposed to light

If light is just a wave, what happens if we turn up brightness?

↳ electrons have more energy

Not the case!

energy of emitted electrons directly proportional to frequency of photons, independent of brightness

1905: einstein proposes particles of light called photons with $E \propto f$

Electromagnetic radiation

Can travel through space

↳ MM experiment

$v = \lambda f$

↳ v is same for all light!

$v = c = 3E8$ m/s

Light

Light is electromagnetic radiation, visible light is EM radiation with $\lambda \approx 400nm - 700nm$

Measuring light

Luminosity: amt. of power object emits

↳ watt

Light intensity: $\frac{W}{m^2}$

Sunlight: $\sim 1 kW/m^2$

intensity $\propto \frac{1}{r^2} \cdot$ luminosity

↳ spherical shells